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THE OIL PROBLEM IN WESTERN AUSTRALIA.

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THE "Search for Oil" in Australia has received the attention of newspapers, technical journals and the public for a decade or two, but little serious thought has been given the subject by the oil fraternity. Late in 1923 the controversy as to the presence or absence of oil in that country had reached a stage where a few widely scattered borings had been made to depths ranging from a few hundred feet to 4,000 feet and had failed to discover more than a few drops of oil. In addition, thousands of artesian water wells sunk at widely separated points in several States had failed to strike oil and only a few of them had encountered as much as 10,000 cubic feet per day of natural gas. Exceptions to the statement are possibly a well or two in New South Wales and the "Roma bore" in southern Queensland. In this last mentioned well some million cubic feet of gas per day were encountered at 3,702 feet from the surface, and when tested was found to contain 1.2 pints of gasoline[1] per thousand cubic feet.

Not satisfied with the quality of the negative evidence or with the lack of knowledge in certain great basins of Permo-Carboniferous, Triassic and other ages, keen-visioned business men and geologists of Australia recommended that these areas be studied. Thus the writer was called to Australia in the employ of Mr. Albert Edward Broué of Sydney, with whose permission the results are published. Mr. Broué was later joined by Mr. Thomas Baker, who purchased an interest in the Westralian areas.

[1] Cameron, W. E., et al., Queensland Geol. Survey, Pub. No. 247, 1915.

In a country the size of the United States the diversity of conditions is too great to permit adequate discussion within the limits of one brief paper.[2] Furthermore, it would be folly to assume that no deposit of commercial oil exists anywhere on the Continent. The instructions concerned localities in Western Australia, and the present paper is limited to this area.

GENERAL GEOGRAPHY AND GEOLOGY OF WESTERN AUSTRALIA.

Western Australia, a state embracing 975,920 square miles, is about one third the size of the United States. It extends from the 14th to the 35th degree of South Latitude; hence its climate ranges from tropical to temperate. The rainfall is more than 40 inches per annum on the southwest coast and over 30 inches per annum over a portion of the extreme north, but throughout about sixty per cent. of the State it averages only about ten inches per year and in some years considerably less.

The State has previously been divided physiographically into the Coastal Plains, the Hill ranges and the Interior Plateaus, as will be understood by reading an outline of the physiographic geology of the State written by Jutson.[3] The rocks range in age from Archean to Recent. The most complete description of the general geology is given by Gibb Maitland,[4] the present Government Geologist, from whom many details stated herein are taken. The geologic relations to the other States of the Commonwealth have been discussed graphically by David,[5] and a bibliography of the geology of the State is supplied by the same writer.[6]

Two thirds of the State, including the major part of the central

[2] An article by E. C. Andrews entitled "Prospecting for Petroleum in Australia" appeared in ECON. GEOL., Vol. XIX., 1924, pp. 157–168.

[3] Jutson, J. T., W. A. Geol. Survey, Bull. 61, 1914, 229 pp., 119 figs., 3 plates.

[4] Maitland, A. Gibb, "A Summary of the Geology of Western Australia," *The Mining Handbook*, Geol. Survey Mem. No. 1, Chapter 1, 1919, 55 pp., 1 map and 80 figs.

[5] David, Sir T. W. Edgeworth, "The Geology of the Commonwealth," Federal Handbook prepared in connection with the Eighty-fourth Meeting of the British Association for the Advancement of Science, 1914, pp. 241–325, 8 illus.

[6] W. A. Geol. Survey, Bull. 1, 1898, 31 pp.

areas, consists of igneous and greatly metamorphosed and altered Archean, pre-Cambrian and ancient Paleozoic strata (Nullagine) of great complexity, to describe all of which would be to embark on a lengthy geologic study, with every prospect that the areal extent, age, and relations of many formations would remain inexplicable. Let the statement suffice that these ancient rocks

FIG. 1. Map of Western Australia showing principal sedimentary areas.

occupy the immense central areas and touch the coast over vast distances, but that they are bordered and indented in places by artesian basins, of which the six areas mentioned in the following table are commonly recognized:

ARTESIAN BASINS OF WESTERN AUSTRALIA.

Names.	Approx. Area (Sq. Miles).
Desert	125,000
Eucla	75,000 *
Coastal Plain Northwest	40,000
Gulf	2,500 *
Ord River	2,000 *

* Comprises only the portion of the basin situated inside Western Australia.

The greater part of the surface of Desert, Northwest, Coastal Plain and Gulf Basins consists of Permo-Carboniferous strata, that of Eucla Basin is Cretaceous and Tertiary, while that of Ord River Basin is Cambrian. Other minor basins exist, as for instance, (1) the Collie coal field in southwestern Western Australia and (2) an inland Tertiary area in the upper Fortesque Valley,[6a] but these are unimportant and will be found not worthy of serious attention after the basins above enumerated have been discussed.

DESERT BASIN.

Description.—The largest artesian basin in the state lies in the southern part of Kimberley and northern part of Eastern Division, extending into the northeastern corner of Northwest Division. About eighty per cent. of this area is inside a vast barren sand-ridge country known as the "Great Sandy Desert" or sometimes the "Kimberley Desert." Only one road traverses the Basin from north to south, this being along the coast.

The only settlements in Desert Basin are the town of Broome and village of Derby, outside of which the white population is not over 100 persons, all of whom live in the Fitzroy River valley and a coastal belt 10 miles wide.

Previous Investigations.—Little geologic work has been done in this desert. Talbot,[7] while engaged in a survey of the Can-

[6a] Numbers in parentheses refer to designations on Fig. 1.

[7] Talbot, H. W. B., "Geological Observations in the Country between Wiluna, Hall's Creek and Tanami," W. A. Geol. Survey, Bull. 39, 1910, 88 pp., 3 maps, 44 figs.

ning Stock Route, crossed the desert from Lat. 23°, Long. 122° 30′ in a northeasterly direction (3, 4). Leo Jones traversed this route, but no report has been published on his observations. The expedition met with disaster, being attacked by aborigines at night; one man was murdered and the leader of the party injured, so that geologic work must have been greatly hampered. A later report by Talbot gives some information concerning a bit of the southwest border of the basin[8] near Throssell (5) and Paterson (6) Ranges. The desert itself is only known to have been traversed half a dozen times, by the two geologists mentioned and intrepid explorers such as Col. Warburton (1873), Hon. D. A. Carnegie (1896–7), R. J. Ankatell (1906) and the Calvert Expedition (1896–7) and practically every party crossing it has met with some fatal disaster.

Only in the northern edge of the basin has any important geologic work been done, for the valley of Fitzroy River (7) is accessible by horse or automobile during the winter or dry season from Derby on King Sound to Halls Creek in Lat. 18° 15′, Long. 128°. The original geologic investigations in this area were made by Hardman,[9] but a good summary report was later given by Jack[10] and its oil possibilities have recently been summarized by Wade.[11] Reports also have been made by Talbot and Blatchford for certain oil interests, but the present writer is unable to agree with the optimism expressed by them.

Physical Characteristics.—The Desert Basin is a topographic as well as a stratigraphic unit, bounded on the north by a descending sandstone escarpment several hundred feet in height, which extends east from a point 77 miles southeast of Broome

[8] "The Geology and Mineral Resources of the Northwest, Central and Eastern Divisions between Long. 119° and 122° E. and Lat. 22° and 28° S.," W. A. Geol. Survey, Bull. 83, 1920, 226 pp., 1 map, 55 figs. and an atlas of 15 plates.

[9] Hardman, E. T., Report on the geology of the Kimberley District, Perth, printed by authority, 1884 and again in 1885.

[10] Jack, R. Logan, "The Prospects of Obtaining Artesian Water in the Kimberley District," W. A. Geol. Survey, Bull. 25, 1906, 46 pp. and Geol. map.

[11] Wade, Arthur, "Petroleum Prospects, Kimberley District of Western Australia and Northern Territory," printed by order of the Senate, Oct. 8, 1924, pp. 10–26.

(8), winding in and out from canyon to canyon and finally losing itself in a maze of table lands 150 to 200 miles farther east (9). A remarkable circumstance is the absence of surface drainage in the desert area 400 miles long by 200 miles wide which constitutes the major portion of the geologic basin.

South of this escarpment the main feature is a vast complex of parallel and rather barren sand ridges trending east and west, interspersed by a few hills, tablelands and rock outcrops and devoid of water except for occasional rock holes and "native soaks." The region is predominantly rough and sandy, but its marginal belts a hundred miles or more in width consist of thick "pindan" (low native bush) or brush. The central portions can be entered only by camel or aëroplane. By diligent effort the party headed by the writer succeeded in driving three motor tractors to the top of the escarpment by way of its western or gently rising termination, then traveled with one of the machines at right angles to the trend of the sand ridges to a point 185 miles southeast of Broome (10). If the desert can be further invaded by car it will be by traveling parallel to these ridges directly inland from Ninety Mile Beach and with an engine consuming a minimum of gasoline and water not yet realized in that region.

Stratigraphy.—The strata of Desert Basin appear to consist of over 12,000 feet of Carboniferous, Permo-Carboniferous and Jurassic sediments, unconformably overlying subjacent Nullagine, Cambrian and possibly Devonian beds. At or near the base of the Carboniferous are perhaps 800 to 1,000 feet of impure red goniatite limestones and massive coral limestones. These rocks and thick interstratified sandy beds are known in literature as the "Lower Series" of the Carboniferous and Permo-Carboniferous, overlying which is that known to all investigators to date as the "Upper Series."

Within a few score feet of the base of this "Upper Series" lies a 30-foot tillite bed (perhaps identical with the Lyons Conglomerate of Northwest Basin) in which large and numerous striated boulders have been found at several places in Fitzroy valley.

Above the tillite lie at least 4,000 feet of massive or flaggy white and gray sandstones, mainly quartzose and unfossiliferous in character, but containing several fossiliferous horizons. So far as observed by the writer, any shales and limestones in this series are thin and unimportant; although shales possibly 50 feet in thickness are reported in the northeastern part of the Basin. There is no doubt that this "Upper Series" is of Permo-Carboniferous age as numerous fossil species have been collected from it and determined by the Government Geologists. Permo-Carboniferous fossils (of previously unknown species but recently correlated by W. S. Dun of Sydney) were also found by the writer 185 miles by motor tractor southeast of Broome and approximately in the center of Desert Basin in a northeast-southwest direction.

Some 50 miles south of Fitzroy River and bounding the Great Plateau of Western Australia on its north side is the great sandstone escarpment already mentioned. Judging by dips prevalent in this escarpment the total thickness of the "Upper Series" may be as much as 10,000 feet, instead of 4,000 feet as previously assumed; moreover, detailed future studies may perhaps reveal an unconformity between the desert beds and this so-called "Upper Series" of the Fitzroy valley, which would limit the "Upper Series" geographically and render necessary a new term for the desert beds.[12]

Above the Permo-Carboniferous are beds of later age. Certain siliceous lateritic and often quartz or flint-capped remnants along and within a few miles of the coast, apparently contemporaneous with beds which reach at least 1,800 feet below sea-level in a Broome artesian well, appear to be Jurassic, inferred entirely on the basis of *belamnites* found in that well. Doubtless an unconformity (aside from the hypothetical one mentioned above) exists between Permo-Carboniferous and Jurassic strata, but has not been discovered, and moreover it is not yet known whether

[12] The term "Desert sandstones" is unavailable, having been used far and wide throughout Australia, but apparently misapplied to strata of Carboniferous, Permo-Carboniferous and Cretaceous-Tertiary ages.

Jurassic beds are limited to less than 2,000 feet or are many thousands of feet thick. So far as lithological character is concerned they do not appear greatly different from presumed Permo-Carboniferous beds of the plateau escarpment, a fact which suggests that these sediments may form a continuous series, although the disparity in age renders such an interrupted cycle of deposition doubtful.

Along the coast, lying above the Permo-Carboniferous and Jurassic rocks, and perhaps extending locally into the interior, are Tertiary and Recent beds of various character but probably seldom if ever over a few hundred feet in thickness.

Geologic Structure.—Desert Basin is not merely a topographic and stratigraphic unit, but also a structural one. Dipping southwest from outcrops and the faulted termination of the Permo-Carboniferous in the vicinity of Margaret River (11) the strata go under this stream and Fitzroy River and thence to the center of the basin, where they are buried by an immense thickness of sandstone. In the plateau, desert and central portions no abnormal or reverse dips are known, although outcrops have been observed at many widely separated points.

In the valleys of Fitzroy River and Christmas Cr. (12), however, a number of excellent structures exist, such as would deserve oil prospecting if other fundamental conditions were in the least favorable. The structures have been mapped in detail by Messrs. Blatchford and Talbot for Freney Kimberley Oil Company.

The geologic structure of this border region constitutes the only fundamental condition which might be considered favorable from a petroliferous viewpoint, but its importance is minimized by the unfavorable nature of other fundamentals. Thus a description of geologic structure is mainly of scientific interest. A post-Cambrian movement has displaced the strata of the present Fitzroy valley along a northwest-southeast line parallel to the bordering mountains, and later movements have folded the "Lower" and "Upper Series" of Carboniferous and Permo-Carboniferous rocks into as high or higher angles than any Paleozoic strata which commonly yield oil. Reverse dips of 3°

to 35° can be seen throughout a distance of 200 miles in the vicinity of the Fitzroy River-Christmas Creek drainage. Four prominent lines of folding in this valley have been studied and mapped by Blatchford and Talbot and checked by Wade, and these attain the character of domes and anticlines at Grant Rg. (13), Mount Wynne, Pool Range and Price's Cr. (7–12). In addition, the strata along the same belt are intruded by a number of pipe-like masses of leucitite of probable Tertiary age.

Reservoir Rocks, Cover and Petroliferous Content.—The question of the porosity of Desert Basin rocks is easily answered, for they consist mainly of sandstones from top to bottom. On the other hand, an absence of cover prevails, for nowhere in explorations of this basin did the writer recognize shale or limestone. The sandstones are mainly soft and porous (except for superficial lateritic silicification due to climatic conditions) and only a few feet of shale are reported, near the base of the "Upper Series" and hence overlain by thousands of feet of intra-basin sandstones. Although sufficient carbonaceous or other organic matter to have furnished the oil may exist in fossiliferous beds of the "Lower Series," none of the outcropping strata shows any authentic trace of oil.

The only "oil indications" ever reported in Desert Basin are at Mt. Wynne (13) and Price's Cr. (12). Fine stringers of much desiccated bitumen were seen by the writer in sandstones—possibly semi-metamorphosed—derived from a "wildcat" well being drilled at Mt. Wynne, 150 miles due east of Broome. Traces of oil were reported by Harry Price—a driller of water wells—from Price's Creek, 260 miles east-southeast of Broome, but have not been confirmed by any one of several geologists who have visited the area in search of the "seepage." Somewhat later the Freney Kimberley Oil Company drilled three tests on Price's Creek dome in "Lower Carboniferous limestone" and noted only traces of bituminous matter and "a smell of mineral oil." Not a trace of natural gas or oil was found in any of the artesian bores at Broome and Derby, and no indications of gas have been reported among hundreds of stock wells 30 to 100 feet deep located

in the coastal belt 10 miles wide extending from Broome southwest to Port Hedland—an air-line distance of nearly 300 miles.

Wells Drilled to Date.—Besides the "Mt. Wynne bore," three "wildcats" at Price's Creek and one at Rough Range, no tests for oil have been made in Desert Basin. Artesian wells have, however, been sunk in several places. Table I is a complete list of borings made for oil and water:

TABLE I.

WELLS DRILLED IN DESERT BASIN.

Description.	Date of Completion.	Depth (Feet).	Result.	Yield* of Water.	Method of Drilling.
Broome No. 1	1906	1,459	Water	142,000	Calyx
Broome No. 2	.....	1,775	"	?	"
Lennard Rd., 67 miles from Derby	1910	3,012	"	140,000	"
Lennard Rd., 82 miles from Derby	1910	391	"	Non-flowing	Hand
Myall's Well, Derby	1910	900	"	Flows to +5 feet	.....
Price's Creek (No. 1)	1922	1,008	Dry	.....	Cyclone
Rough Range (No. 2)	1923	728	"	.....	"
Price's Creek (No. 3)	.....	809	"	.....	"
Price's Creek (No. 4)	.....	444	Water	Non-flowing	"
Mt. Wynne	1925	1403+	"	Plenty	Calyx

* In gallons per day when allowed to flow uncontrolled.

Summary.—The minute nature of the oil indications in the several wells drilled, the apparent total absence of natural gas, uncertainty as to the actual existence of any "surface indications," lack of cover, prohibitive thickness of sandstone over enormous areas and somewhat unsatisfactory source of origin are collectively considered unfavorable to the commercial occurrence of oil in Desert Basin.

NORTHWEST BASIN.

Description.—A sedimentary area 400 miles in length from north to south and 175 miles in greatest breadth borders the Indian Ocean between the Northampton mining area on the south and Northwest Cape and the mouth of Ashburton River

on the north. This basin includes the greater part of Lyndon, Gascoyne, Murchison and Edel Districts of Northwest Division, but overlaps into the north end of Southwest Division. The principal City is Carnarvon, beside which the only settlement is the village of Onslow. The area is largely covered by great sheep ranches or "stations." One main "motor road" traverses the area from north to south, with branches to the various "stations."

Stratigraphy.—The stratigraphy of Northwest Basin may be likened in general to that of Desert Basin, with which it was doubtless once connected, either about the north end of the intervening crystalline and metamorphic plateau or over its crest, which has a width of 300 to 400 miles. As in Desert Basin, there is a "Lower Series" and an "Upper Series" of Carboniferous and Permo-Carboniferous age, and these are predominantly sandy as in Desert Basin. The "Lower Series" contains some limestones, calcareous sandstones and perhaps thin shales, but no shales of importance were seen. The combined beds are known to be at least 2,000 feet thick and are probably much thicker.

As in Desert Basin, the approximate top of the "Lower Series" is marked by a great tillite bed—in this case the Lyons Conglomerate—which can be traced from north to south by a practically continuous outcrop for over 200 miles and constitutes a prominant key bed. As in Desert Basin, the age of the "Upper Series" is determined by Permo-Carboniferous fossils. On the Permo-Carboniferous rest limestones and siliceous beds of Jurassic, Oligocene and later ages, which likewise are several thousand feet thick on the coast and form Peron Peninsula (14), Dirk Hartogs Island and the large peninsula which is terminated by Northwest Cape (15).

Geologic Structure.—As is the case in Desert Basin, abundant structures exist, both in the strata of Carboniferous age which outcrop on the east side of Kennedy Range (24) and also in Oligocene sediments of the coast. In the last mentioned belt an

immense anticline forms the peninsula west of Exmouth Gulf, terminated by Northwest Cape (15) and made almost inaccessible by great sand ridges and minor folds which may be repeated at intervals southeast to near Winning Pool. East and north of Kennedy Range in the eastern part of the basin less prominent anticlines were found—one noticeable dome involving a core of Lyons Conglomerate. Any or all of these structures might be of interest if other conditions were at all favorable; but as is the case in Desert Basin, no other single fundamental factor appears satisfactory.

Reservoir Rocks, Cover and Petroliferous Content.—There is no question of porosity, for thousands of feet of white or gray sandstones exist, similar to those in Desert Basin, suitable for carrying oil under other circumstances. They are mainly siliceous and comprise the entire Carboniferous and Permo-Carboniferous portion of the stratigraphic section to the exclusion of shales, and few if any cover rocks are known. In fact, only a few feet of shale were actually seen or authentically reported in the basin, and it seems a physical impossibility for oil to remain in these rocks even if it were ever formed in them. The immense limestones of later age may have formed oil, which, however, cannot have remained in quantity, for these limestones are everywhere open and porous, and, so far as observed, are not overlain by shales or other impervious rocks.

Enquiries were made for reports of actual oil, and in one or two instances rather vague statements were received of showings on the surface of the outlets from artesian wells, but in every observed case the ingredient was found to be only a trace of iron oxide or nothing at all.

Wells Drilled to Date.—Nowhere among the two score, more or less, artesian wells was any trace of oil or natural gas to be found.[18] These wells range from a few hundred to over 3,000 feet deep and yield in one instance as high as 2,000,000 gallons of

[18] The nearest to an actual gas occurrence were several reported "flashings" of gas in water emerging from flowing wells; but several of these were tested and not found to flash noticeably at the time.

water per day.[14] In addition, a few of them furnish definite information relative to stratigraphic conditions and serve to confirm conclusions arrived at from superficial studies. It is true that in some cases shaley beds were reported; but in that region any fine grained material has often been termed "shale," hence such reports were not considered important. Moreover, if oil existed in commercial quantity anywhere in Northwest Basin, it would seem that some trace of oil or gas should have been found in one or more of the numerous wells.

COASTAL PLAIN BASIN.

Description.—Coastal Plain basin is practically a continuation of Northwest Basin, formerly connected over and now connected about the Northampton mineral and granitic area. The basin lies entirely in Southwest Division. It has a length of 350, and maximum breadth of 70 miles. It is the only basin in Western Australia that is moderately settled in any part, for it contains the capital City of Perth, with 155,000 inhabitants, Geraldton, and some smaller towns. The greatest amount of detail in literature pertaining to Coastal Plain Basin is found in a paper on the Irwin River area.[15]

Stratigraphy.—The strata are Permo-Carboniferous, Jurassic, Cretaceous and Tertiary in age. Permo-Carboniferous beds form a narrow outcrop along the eastern edge of the basin throughout the northernmost 75 miles from a point west of Mullawa to a point east of Arrino. As in Northwest and Desert Basins, the Permo-Carboniferous is divided into a "Lower" and an "Upper Series," of which the "Lower" is here believed to consist predominantly of limestone and the "Upper" predominantly of sandstone. The strata comprise sandstones, limestones, and occasionally coal beds and shales, which are practically

[14] Reports of A. Gibb Maitland in publication of the First, Second and Third Interstate Conferences on Artesian Water, with accompanying maps, sections and other illustrations.

[15] Campbell, W. C., "The Irwin River Coalfield and the Adjacent Districts from Arrino to Northampton," W. A. Geol. Survey, Bull. 38, 1910, 108 pp. 6 plates, 53 figs.

absent farther north. About the middle of the " Lower or limestone " series is a glacial boulder bed, which is practically continuous from north to south and forms a good key horizon. It appears to be the southern extension of the Lyons conglomerate found along the east side of Northwest basin.

The thickness of Permo-Carboniferous beds is unrecorded and may not amount to more than a few hundred feet. The largest Carboniferous area is in the extreme southwest part of the Continent, between Geographe Bay (17), Indian and Antarctic Oceans and covers about 700 square miles, bounded by granite on the east and west. The depth of rocks in this south area may not be great.

The greater part of the surface of Coastal Plain Basin is composed of rocks of Jurassic age, which overlie the Permo-Carboniferous strata with marked intervening unconformity. The Jurassics are represented by oolitic limestones, clays, sandstones, conglomerates, and some lignites. They are supposed to be at least 3,000 feet thick in the vicinity of Geraldton, as determined by surface outcrops and a boring.

Of the Cretaceous beds less is known, for they appear to be exposed only in a small area near Gingin, about 50 miles northeast of Perth. The constituent beds are glauconitic and shaley limestone, chalky clay, chalky limestone; their composition and general character suggest that in reality some of the rocks classed as Jurassic in Northwest and Desert Basins may later be determined to be Cretaceous. Borings at Perth, Claremont, Dandarraga and on Rottnest Island near Perth passed through perhaps 1,000 feet of such strata.

Tertiary rocks also are present along the coast, and may be of some stratigraphic importance, but are not in all cases differentiated from Cretaceous beds which occur in the same areas. It is probable that some of the coastal Tertiary beds may belong to the same Oligocene formation as that recently identified in the peninsula west of Exmouth Gulf in Northwest Basin.

The coastal deposits are overlain locally at Black Point and elsewhere in the extreme south (18) by basaltic flows.

The Geologic Structure.—As is the case in the Northwest and Desert Basins, the rocks dip generally west. The basin is bounded on the east by a great fault line. A small area of Coastal Plain Basin comprises an anticline which is mapped by the Government Geologist on Irwin River 40 miles northeast of Dongara and 50 miles southeast of Geraldton. The Permo-Carboniferous beds are uplifted in a broad gentle fold surrounded by the overlying Jurassics.[16] It is possible that other anticlines may occur in the basin, but they are not recorded. Like the structure of Desert and Northwest Basins, that of the Coastal Plain basin may be said to be moderately satisfactory from the standpoint of oil exploration, but the value of this circumstance seems to be nullified by the absence of other favorable fundamentals.

Summary.—The Coastal Plain basin contains some coal beds and a considerable thickness of shales, which are generally absent farther north and it has some anticlinal structure. It may therefore be said to be the least unfavorable of any Westralian basin. Nevertheless, none of the numerous wells from a few hundred to 2,000 feet deep which have been sunk for artesian water has reported any oil or gas, but, on the contrary, these wells flow from 100,000 to 1,870,000 gallons daily of pure water. No seepages or oil indications are anywhere known. Under the circumstances, the basin cannot be considered favorable for oil.

Oil Excitement in the Past.—In the Warren River district 45 miles southeast of Augusta at the extreme south end of Coastal Plain Basin, excitement was once caused by a reported discovery of oil and three or more test wells were sunk by the Westralian Mining and Oil Corporation on the Warren River not far from the Darling fault. One of these borings passed out of Permo-Carboniferous beds into detrital granitic material and continued in such material to the bottom of the hole at 1,719 feet.

In the first official report on this area the Government Geologist [17] declared that " no petroleum has been discovered in the dis-

[16] *Op. cit.*, Pl. V.

[17] Maitland, A. Gibb, " The Reported Petroliferous Deposits of the Warren and Donnelly Rivers," Ann. Rept. W. A. Geol. Survey, 1902, pp. 13 et seq.

trict" and that the structure appeared unfavorable. All subsequent reports are of similar tenor.

About 1902–3 sensational reports appeared in the press and in pamphlets circulated by promoters and by self-styled "oil experts" calling attention to bituminous deposits found along the coast between Capes D'Entrecasteaux and the Leeuwin, and traces of oil were reported "in the sand dunes" and floating on the sea. Similar reports of oil on the south coast of Australia have arisen every year from Western Australia eastward into Victoria, a distance of over 1500 miles. They have been due in part to asphaltum washed up by the waves in sometimes large masses and at widely separated points; but asphaltum has never been found inland or away from points accessible to wave action. The literature on these occurrences is voluminous, and the falsity of the Australian derivation of this material has been shown.[18] According to Woodward, the south-southwesterly gales, striking obliquely on the Antarctic current coming from the southeast is the agency which has deposited the material on the Australian coast.[19]

An oil-like scum found on certain inland waters near the south coast is likewise not an oil indication, but appears to be identical with the material generally known as "coorongite," a derivation from certain plant growths in stagnant brackish waters[20] and in other cases it is ordinary ferric-hydroxide. The problem of the district is discussed by Woodward,[21] who finds nothing favorable in the district.

A paper on a portion of this district, not available for reference herewith, is that by Maitland;[22] and another paper by Clark[23] refers to the same locality.

[18] Ward, L. Keith, Geol. Survey S. A., Bull. 2, 1913, pp. 13–15.

[19] Woodward, H. P., Bull. 65, W. A. Geol. Survey, 1915, p. 24.

[20] Ward, *op. cit.*, pp. 15–20.

[21] Woodward, H. P., "The Reported Petroliferous Area of the Warren River District (Southwest Division)," W. A. Geol. Survey, Bull. 65, 1915, 54 pp. and 2 maps.

[22] Maitland, A. Gibb, "Petroleum Prospects of the Busselton Neighborhood, Southwest Division," printed by authority, Perth, 1921.

[23] Clark, Edward de Courcey, "The Reported Occurrence of oil near Wonnerup, Southwest Division," printed by authority, Perth, 1916.

ORD RIVER BASIN

Description.—Ord River Basin (19) is an elliptical area, about 80 miles in length in a northeast-northwest direction and 40 miles wide, through which flows Ord River. It has been ably discussed by Wade.[24]

Geology.—All rocks of this basin, estimated by Wade as at least 8000 feet thick, are believed to be of Cambrian or pre-Cambrian age. They consist, from below upwards, of the Albert Edward Range series of quartzites, silicified limestones and cherts (2,000 + feet) at the base, chocolate colored conglomerates and sandstones (200 feet), and vesicular basalts (3,000 to 4,000 feet) overlain at the top by 1,700 feet or more of flaggy sandstones and limestones. The basin is completely surrounded by basalt, which forms a highly elevated rim dipping sharply towards the center from all sides. The border dips are steep to vertical, while in the center of the basin the beds are practically flat.

Other Conditions.—It is significant that basalt comprises at least half of the basin system of rocks. Still more remarkable is the fact that bitumen occurs in two localities in its north rim—being found in small quantities in vesicles, cracks and pipes of the basalt.[25] This bitumen is now considered an inspissated petroleum derived from overlying Upper Cambrian beds.

The beds overlying the basalt are in places crowded with organic remains and would be amply able to provide a source of oil. They furnish no indication of its present existence, however, and all oil has evidently disappeared during the ages. No traces of bitumen have been reported from the junction of basalt and limestone, and the other rocks are not perceptibly petroliferous. Suitable structures are not reported, although they might exist. Even were oil still present, possible storage beds are not reported. In view of the general absence of commercial oil in Cambrian strata

[24] Wade, Arthur, "Petroleum Prospects, Kimberley District of Western Australia and Northern Territory," printed by order of the Senate, Oct. 8, 1924, pp. 26–32.

[25] Mahoney, D. J., in a private report made to Okes-Durack Oil Company in 1923.

elsewhere in the world and of the minute nature of the indications, little hope exists of finding commercial oil in Ord River Basin.

GULF BASIN

In the northeast corner of the State and directly east of Wyndham is an area scarcely 25 miles wide, extending east as far as Queens Channel in Northern Territory and northeast to Anson Bay—a distance of 200 miles—in which the strata are mapped as Permo-Carboniferous.

Near Port Keats, 130 miles in air line northeast of Wyndham, borings for coal reached a depth of 1,500 feet[26] and appear to have encountered the granite floor. No traces of petroleum or gas are reported. So far as known, the strata in this narrow belt dip seaward at slight angles, and there is nothing to indicate the occurrence of petroleum.

From 1897 to 1907 three diamond drill tests were sunk at the town of Wyndham to 690, 1,337 and 203 feet deep respectively, resulting in failure to find water by the first two and obtaining an artesian flow of 700 gallons per minute from No. 3 (known as the "1-mile well").

EUCLA BASIN

Description.—In Eucla Division of the extreme southeastern part of the State is an area 300 miles from east to west and 200 miles in maximum breadth, known as Eucla Basin, extending eastward into South Australia for over 150 miles. The area is widely famed as the Nullabor Plains (meaning "not a tree") or Premier Downs, a flat treeless and uninhabited waste. There are no rivers on these plains.

North of the Trans-Continental Railway the region has been visited only by a few persons, of whom the most notable are E. Giles (1875), D. Lindsay (1891–2), Mason (1896), Talbot and de Courcey Clarke (1916). This basin is the subject of a

[26] Jensen, H. I., The Northern Territory, Proc. Roy. Geog. Soc. Australasia, Vols. XXXII.–XXXIII., p. 14.

paper by Gibb Maitland,[27] which, however, is not available for use herewith.

Stratigraphy and Structure.—The strata consists mainly of caverous limestone ("Eucla limestone") of Miocene age, soft sandstones, clay shales and occasional conglomerates, disclosed in deep borings. Its geographic surface is the "Eucla limestone Plateau," 200 to 400 feet above sea level in the Hampton Range escarpment (20) on Great Australian Bight, rising to 450 and 650 feet at the Trans-Continental Railway (21) and 1,000 feet above sea level farther north.

All of the beds dip southwards towards the Bight, and where exposed on the coast they are flat lying in an east-west direction. Underlying the Pliocene at a depth of 1,200 feet, the Miocene beds have been shown by borings to rest on Lower Cretaceous strata[28] upwards of 600 feet thick, consisting of calcareous glauconitic mudstones, claystones, shales, glacial boulder beds, and dolomitic limestones. Below the Cretaceous beds are the granitic rocks that border the basin on the west and have been reached in several borings. Cretaceous rocks are also supposed to outcrop over an area to the north of similar size to the Nullabor Plains, but little studied, as the region is rough, waterless and accessible only with the greatest difficulty.

A boring at Albalakaroo 40 miles east of the frontier in South Australia bottomed on granite at 1,073 feet.[29]

Summary.—No reports of oil have been received from Eucla Basin, and the known thickness of rocks does not warrant the assumption of oil probabilities, structure appears conspicuous by its absence and suitable combinations of porous beds with impervious cover have not been reported. Water wells range in depth from 300 to 2,500 feet and by pumping they supply from 30,000 to 250,000 gallons per day. Some of the wells drilled on

[27] Maitland, A. Gibb, "Petroleum Prospects on the Nullabor Plains—Eucla Division," printed by authority, Perth, 1919.

[28] Talbot, H. W. B., and Clark, E. de C., W. A. Geol. Survey, Bull. 75, 1917, pp. 105–111.

[29] Maitland, A. Gibb, W. A. Geol. Survey, Bull. 26, 1907, p. 62.

the South Australia side of the boundary have yielded salt water, but no oil was found.

MINOR BASINS.

The Collie River coal field (1) of Permo-Carboniferous age [30] lies east of Bunbury and south of Perth and has an area of perhaps 500 square miles. The beds consist of shales, sandstones and conglomerates which rest on cherts and ancient crystallines. The boundary of the basin is nearly everywhere marked by faults, certain of which have thousands of feet displacement. This area seems to have no special claim to attention.

In the upper part of the Fortesque River valley (2), midway between Desert and Northwest Basins and 150 to 300 miles from the coast is an area of about 6,000 square miles of Tertiary and post-Tertiary beds, but little is known of it. Other minor Tertiary areas are found on the Indian Ocean coast, on islands between the Desert and Northwest Basins and again on the coast of the Antarctic Ocean between Eucla and Coastal Plain Basins.[31] These beds appear to be only a few hundred feet thick.

Some tillite beds of unknown age have been found by the writer on Braeside station (22), 200 miles in air line southeast of Port Hedland and probably 50 miles from Desert Basin, but these likewise are unimportant.

DRILLING OPERATIONS OUTSIDE THE BASIN.

Desultory drilling has been done near Albany on Antarctic Ocean 240 miles southeast of Perth, but the boring bottomed on granite at 237 feet and is said not to have penetrated any stratified rocks except 135 feet of clays carrying petrified wood and pyrite. This locality is entirely granitic with merely a fringe of eolian and other Recent deposits and has been unfavorably re-

[30] Maitland, A. Gibb, Bull. 26, W. A. Geol. Survey, 1907, pp. 57–60.

[31] Jutson, J. T., and Simpson, E. S., *Jour. and Proc., Royal Soc. W. A.*, Vol. II., 1917, pp. 48–50.

ported on by the Government Geologist.[32] Many borings have been sunk for water throughout the inter-basin areas and in none of them has oil been reported or would it be expected.

CONCLUSION.

Adequate attention appears to have been given the search of oil in Western Australia to justify an opinion as to the probable success of drilling operations in the State. The four principal artesian basins have been personally visited by the writer, he has carefully studied all conditions and considered the supposed favorable evidences offered by interested parties. Seldom in his experience has any such discouraging set of conditions been found. Somewhere within the limits of Western Australia a small pool of oil may exist, but this is considered unlikely; and as to the presence of any field of commercial proportions, there is not the least evidence, whereas a multitude of facts are opposed to the supposition.

The writer regrets that, in refuting the supposed occurrence of petroleum in Western Australia, he finds it necessary to oppose the opinions of many government and private geologists of that State and many men of other professions who have taken a stand that it will ultimately be found. He realizes that throughout Australia he may be accused of attempting to suppress "legitimate development"; but he is convinced that expenditure in drilling for oil in that State is useless and should be discouraged. He therefore offers his regrets to his confreres in that country with whom he cannot agree, and urges that they will visit and compare conditions in existing oil fields of the world before advocating further expenditure in Western Australia.

The writer is indebted to many persons for helpfulness in arriving at the conclusions herein. Certain reports of travelers, taken in connection with the occurrence of vast Permo-Carboniferous, Jurassic and Tertiary basins, offered hope of favorable

[32] Maitland, A. Gibb, "The Geology of Princess Royal Harbour, with Reference to the Occurrence of Oil," W. A. Geol. Survey, Bull. 26, 1907, pp. 27–33 and geol. map.

discoveries. A genuine need for the investigation existed, as explained on the first page, and the time and cost should not be regretted.

Prof. Sir Edgeworth David—the senior Australian geologist—has been encouraging in this effort to solve the oil problem of a state, and Messrs. A. Gibb Maitland, E. C. Andrews and L. Keith Ward, Government Geologists of Western Australia, New South Wales and South Australia respectively, have furnished useful hints, been helpful in consultation, and have otherwise been of great assistance. The members of the State Lands Department have kindly furnished maps marked to date with routes and data, and made suggestions for desert travel.

50 CHURCH ST.,
NEW YORK CITY.

THE FORMATION OF CERTAIN ORE BODIES BY MINERALIZATION STOPING.[1]

Brecciation Due to Removal of Support by the Dissolving Action of Solutions During an Early Stage of Their Activity, Followed by Mineral Deposition in the Brecciated Mass at a Later Stage.

AUGUSTUS LOCKE.

Introduction.

Heretofore, the explanations of certain mineral pipes, of which the famous Pilares is an example, have not been wholly satisfactory. Furthermore, the explanations of a related ore body type, represented by Bingham and Miami, are in a similar condition. The writer has had an opportunity to study the Pilares and several deposits resembling it and has come to a definite conclusion regarding their origin. He has studied also most of the well-known deposits of the other type and feels that their origin is similar to that of the Pilares, though the proof is less clear. Both are attributed, in brief, to removal of rock along trunk channels by rising solutions during an early stage of their activity, collapse and

[1] The writer acknowledges his indebtedness to T. J. Hoover, who permitted the study of specimens in the laboratories of the Stanford Mining School; to Charles Dobbel, H. W. Morse, Nahum Sabsay and M. N. Short, who carried on studies of specimens; to Guy N. Bjorge, who supplied information from Pilares; to H. M. Kingsbury, who supplied a photograph, drawings, and information from Bisbee; to Ira Joralemon, who supplied information from the Copper Creek district near Mammoth, Arizona; to B. S. Butler, L. C. Graton, Adolph Knopf, Waldemar Lindgren, G. F. Loughlin, F. L. Ransome, and A. C. Spencer, with whom the writer has carried on discussions of this subject; to the Phelps-Dodge Corporation, which permitted the publication of information concerning its property in Bisbee and Nacozari; to the Ibex Gold Mining Co., which permitted the publication of information concerning its property in Leadville; and to the United States Geological Survey, which took pictures of specimens and permitted their use here.

brecciation of the rock thus left unsupported, and deposition of ore and gangue minerals in the brecciated mass.

The two types of mineral body mentioned above may both be termed *disseminated mineral deposits;* for both consist of ore and gangue minerals widely scattered through large masses of brecciated rock. Regarding both, the same obvious question must be asked: "Why were the minerals disseminated, rather than aggregated or disposed in linear or in tabular bodies?" Or, to put it one step farther back, "Why was the rock, into which the mineral was to be received, broken into small, angular pieces, with a lavish expenditure of energy, rather than along a few principal planes of movement?"

Because, therefore, the mineral pipe is a special case of disseminated mineral deposit, not formless like the great copper bodies of Bingham, but regular in outline, its well-defined structural characteristics will be used in this paper as the principal evidence on the questions at issue. Answered for the one type, these questions will necessarily, in some degree, be answered for the other.

The Pilares Deposit.

The Pilares mine, Sonora, Mexico, occupies a body of rock which has the familiar fracturing mentioned above. The rock may be described as *crackled:* that is to say, it is broken into small, angular fragments which for the most part lie closely fitted together.

The surrounding surface shows flat-bedded latite tuff, 300 to 500 feet thick, which rests conformably on andesite tuff. The contact between the latite and the andesite is known in detail within the mine and can be used as a marker to indicate any subsidence which may have occurred there. No pre-ore intrusive has been positively identified and much supposed monzonite has proved to be fragmental. The crackled body, a vertical pipe cut in these rocks, has a horizontal section of regular, oval outline, measuring 1000 by 2000 feet; it is developed to the depth of 1800 feet.

Within this pipe, the rock has undergone alteration similar to that of the Bingham deposits, and its crackling is similar, though a little coarser. It carries pyrite, disseminated and on cracks, accompanied by quartz and sericite or chlorite. It carries also chalcopyrite, in separated, thin veinlets, but here and there in

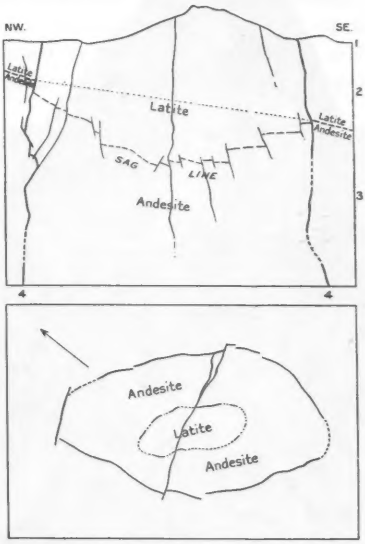


FIG. 1. Plan and section of the Pilares pipe, Sonora, Mexico. 1, surface; 2, latite; 3, andesite; 4, walls of pipe. (Adapted from Bjorge.)

veinlets sufficiently thicker and nearer together to make ore. But most of the ore lies, not in the body of the pipe, but out against its vertical walls; and not in merely crackled rock, but in jumbled breccia or rubble.

This jumbled breccia or rubble forms an envelope surrounding the pipe, some 50 feet thick along the side walls of the oval but thicker in the ends, making great, irregular, steep masses there. It resembles in pattern the broken rock filling a caved stope. Its

fragments are similarly unsorted and they similarly range in size from mere slivers to pieces 10 feet in diameter. The space between the fragments, now surviving as quartz-lined vugs, or filled with quartz, pyrite, and chalcopyrite, attains a similar maximum

FIG. 2. Pilares latite ore. $\times 2/3$. (Photo by U. S. Geol. Survey.)

of about 30 per cent. of the volume. The ore has a maximum grade which accords with the filling of 30 per cent. of voids by chalcopyrite. It is a striking fact that the mine, even near the surface where enriched by chalcocite, has yielded little ore of smelting grade. The ore, as broken, is thickly crowded with small rock fragments, like a piece of concrete masonry, and cannot be hand-sorted up to a rich product. It is clear that the min-

eralization and the movement of the fragments overlapped and that the fragments, though chiefly shaped by fracture, were in some degree shaped by attrition and corrosion. It is clear also that the chalcopyrite arrived, with quartz and pyrite, as the last episode of the mineralization, after the rock had been well altered and the movement had ceased; and that, though partly replacing the rock, it was deposited mainly in the open spaces previously formed by the rotation, attrition, and corrosion of the rock fragments. The statement of the proportions between

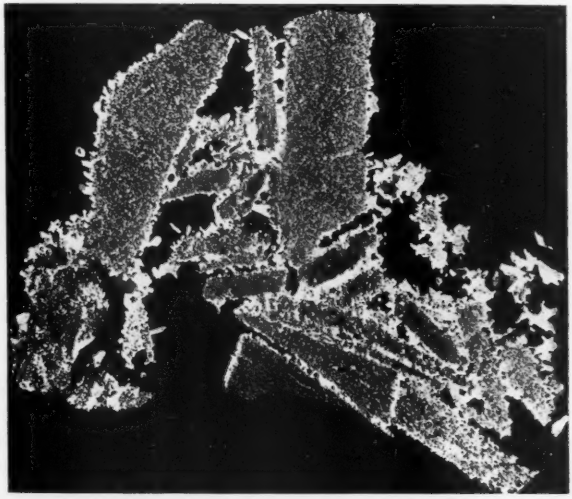


FIG. 3. Pilares latite ore. ×6. The cavities are lined by quartz crystals filled by chalcopyrite. (Photo by U. S. Geol. Survey.)

"replacement" and "open space filling" must depend on the sense in which those terms are used. In the ordinary sense, the quartz, sericite, chlorite, pyrite, and minor chalcopyrite, of which the rock fragments are now made up, would be regarded as "replacements," and the interstitial quartz, sericite, pyrite, and chal-

copyrite would be regarded as "open space fillings." The chalcopyrite is conspicuously localized by cracks. It may invade the walls for a short distance or wrap about a rounded-off end of a rock wedge. But the open spaces determine where it is to lie. And no reason has been found, in the very numerous specimens examined, to doubt that the fragments, previous to the advent of the chalcopyrite, were supported against each other; nor to believe that the interstitial chalcopyrite did very much more than fill in the open spaces and pry off small slabs of rock.

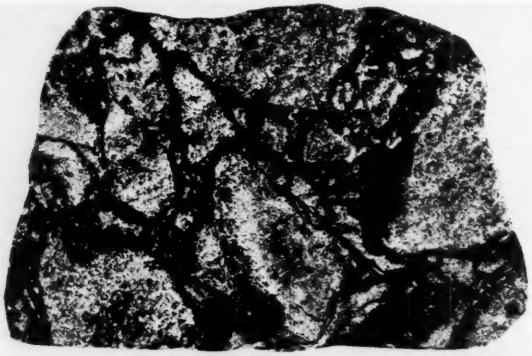


FIG. 4. Tourmaline and pyrite cementing fragments of granite which contain pyrite and have outlines more rounded than those shown in Fig. 2. × 3/4. Wickes, Montana. (From the collection of the Department of Geology, Univ. of California.)

The resemblance of the ore breccia to the filling of a caved stope stimulates the search for other evidences of subsidence. Such evidences are yielded clearly. The latite-andesite contact, 300–500 feet deep outside the pipe, sags inside as an inverted cone to the 900-foot level and shows over the entire oval an average subsidence of 200 feet. This subsidence was found by G. N. Bjorge to have occurred on numerous cracks of pre-ore origin. Of these the most continuous are marginal, marking the wall itself:

the individual wall cracks, carrying gouge, persist for distances as great as 500 feet without interruption around the curved, oval outline of the pipe, and when one dies out another is found in a different plane nearby. They make the boundary between the solid wall rock of the surrounding country and the subsided pipe of crackled rock within, and the jumbling of the rock fragments at this boundary may be likened to the drag of ore on the side wall of a bin.

Not only do the jumbled breccia and the cone of subsidence accord with the effects produced in the caving of a stope, but we find that the steep pipe form itself is an equally true analogy. Studies of several months duration, made on the subject of caving in Bisbee by H. M. Kingsbury, E. H. Wisser, and the writer, have shown that when an ore body collapses, whether through mining of the ore or through shrinkage in oxidation, the roof usually fails by caving and domes up until the space below it becomes filled to the maximum thickness of 100 feet with jumbled rock fragments; and that, when the caved material attains a certain critical size, steep cracks, curving in plan and enclosing a circular or oval pipe, spring upward from the margins of the dome. These cracks may ascend even several hundred feet to the surface, undiverted from their course by preëxisting structures. Except in cases of overlapping effects of several ore bodies, they make a curved outline indicating the individual area below in which lies the focus and place of shrinkage.

In short, the pipe form and the steepness of attitude, which are the main peculiarities of the Pilares as contrasted with other disseminated mineral deposits, have been produced in Bisbee by oxidation and mine subsidence. It is true that the Pilares pipe is uncomplicated by overlapping circles of subsidence and that its walls maintain their verticality and their envelope of jumbled fragments with a striking regularity. It is true, further, that the Bisbee subsidence pipes are as a rule less regular and that they come down with little crackling and sagging in the middle. But the general outlines of result in the Pilares and Bisbee cases are similar.

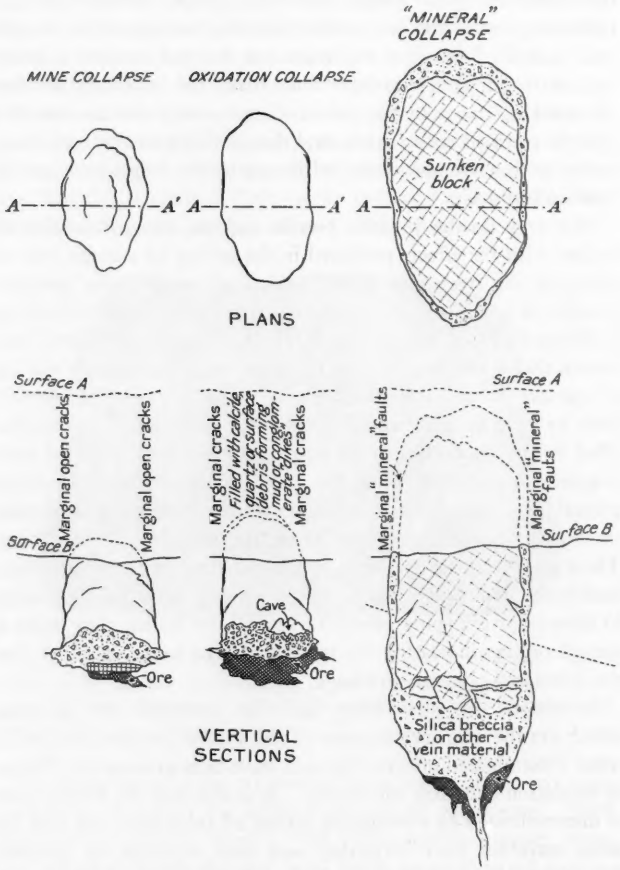


FIG. 5. Sketch plans and sections showing mine, oxidation, and hypogene, or "mineral," collapse. (Drawn by Kingsbury.)

There is indeed reason for astonishment at this similarity, for a whole series of possible results can issue from the same general process. In rock that is plastic, subsidence can make, not a pipe,

FIG. 6. Jumbled fragments of porphyry, broken by the shrinkage during oxidation of an underlying ore body in limestone, and cemented by calcite and aragonite. (Photo by Kingsbury.)

but a sag-basin without marginal faults. Or, given a pipe, the effects will vary with the speed of the subsidence; for, if rapid, it tends to cause the ground to settle in a solid block; if slow, it tends to cause numerous, successive, small adjustments by which the block is broken in many pieces.[2] Or, the effects will vary with

[2] See Eavenson, Howard, N., "Report of Subcommittee on Coal Mining to Committee on Ground Movement and Subsidence." *Trans. Am. Inst. Min. and Met. Engrs.*, February, 1926.

the size: 100 feet in diameter, the pipe tends to be jumbled throughout; 1,000 feet in diameter, it may drop as a cylinder and may be merely cracked without rotation of its pieces. In any case, the pipe may terminate upward in a dome or arch before it reaches the surface.

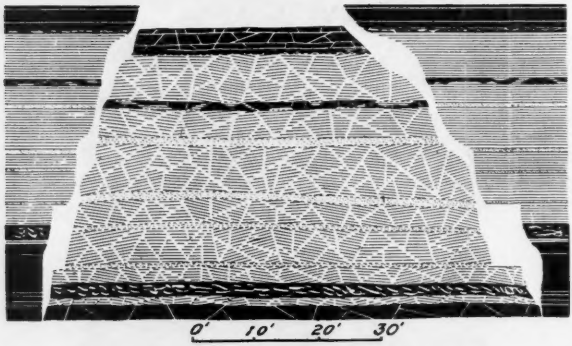


FIG. 7. True section showing subsidence of shale, sandstone and coal strata on removal of pillars in the Pittsburgh seam, Georges Creek region, Maryland. (Adapted from Eavenson.)

If the overlapping subsidence circles be sufficiently complicated, no regular marginal cracks will be established, the pipe form will fail to develop, and the result will be the irregular stockwork or disseminated mineral body which is more common than the pipe itself.

SUBSIDENCE AS A FACTOR IN THE MINERAL PIPES.

The explanations commonly offered for the Pilares pipe are:

1. It was localized on the intersection of two sets of fractures.

2. It is a plug of rock pushed up by the pressure of an intruding fluid and then drawn back like a cork when that pressure declined.

Were the Pilares the only pipe to be accounted for, one or both of these explanations might seem to apply. But there are many

TABLE I.

A FEW OF THE BETTER KNOWN MINERAL PIPES.

	Rock.	Metals.	Attitude.	Horizontal Dimensions (Feet).	Depth of Mining (Feet).	Top.	Bottom.
Bassick, Colo.	Volcanic agglomerate	Au, Pb, Zn	85°	30 x 100	1,400	Eroded	Not found
Bull Domingo, Colo.	Schist	Ag, Pb, Zn	80°	50 x 80	550	Eroded	Not found
Catalina, Son.	Tuff	Pb, Zn	Steep	About 300 x 400	About 600	Eroded	At about 500′ rough floor
Cactus, Ut.	Monzonite	Cu	Steep	200 x 800	1,000	Eroded	Diminishes below 600′
Copper Prince, Ariz.	Granite	Cu	Steep	100 x 200	450	Eroded	At 450′ has tapered to vein
Cresson, Colo.	Fragmental volcanic	Au	70°	500 x 800	2,200	Eroded	Not found
Duluth, Son.	Tuff	Cu	80°	300 x 1,000	1,000	Eroded	Not found
Patch, Colo.	Granite gneiss	Ag, Pb, Zn Cu	Steep	400 x 800	1,600	Eroded	Not found
Pilares, Son.	Tuff	Cu	90°	1,000 x 2,000	1,800	Eroded	Not found
South Ibex, Colo.	Quartzite	Au	70°	60 x 120	900	At 450′ ends upward in dome	Not found
Southwest, Ariz.	Limestone	Cu	Steep	1,200 x 2,000	1,000	Eroded	At about 500′ rough floor following bedding.

other pipes and, for a whole group, all having the extraordinary qualities of steepness and of oval or circular outline, they utterly fail. An intersection of fractures would be vertical only here and there. And were the pipes created by pressure below, they would of necessity bend, flare and contract, now going off flat along the contact, and now turning sharply sideways or upward.

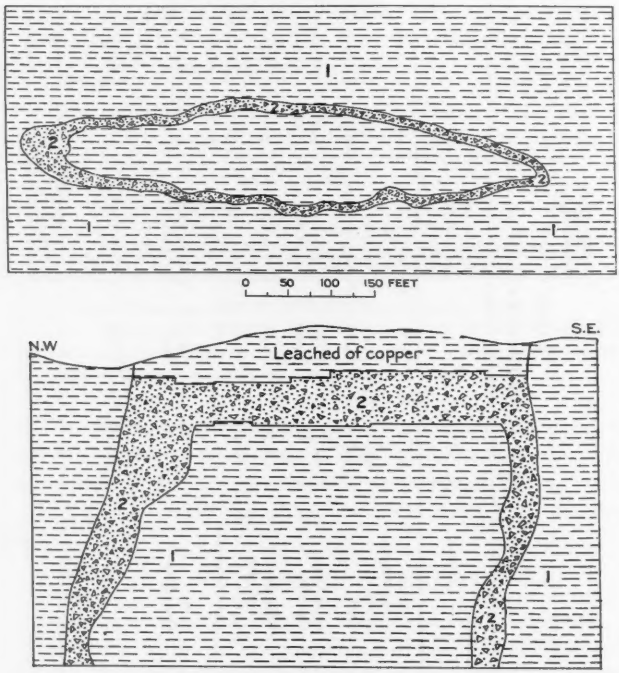
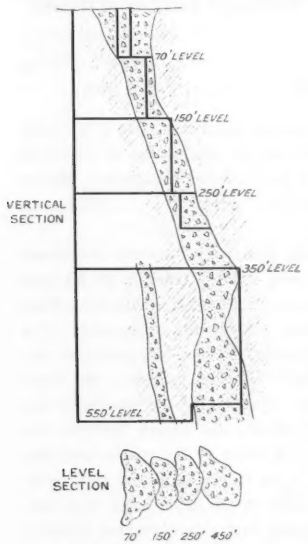


FIG. 8. Plan and vertical section of the Duluth pipe, Sonora, Mexico. 1, tuff; 2, rubble or ore in pipe.

Note: Although this pipe is commonly mentioned as an intrusive plug, H. M. Kingsbury and the writer found the rock within it to be, at least in part, bedded and fragmental.

Their regularity and verticality would not at all accord with expectation, for these qualities could result only from a peculiar succession of accidents, strung together, and many times repeated.

In explanation of the characteristics of steepness and pipe form, the writer has been compelled to seek some other principle and he has found only one that is satisfying. This is the *movement of rock under the impulse of gravity.* In accordance with this principle, the pipes are regarded as having the simple, dominant genetic feature of subsidence, and they are characterized



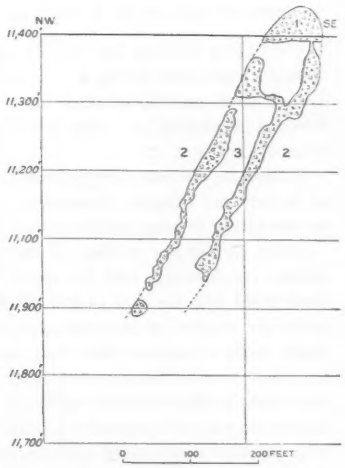


FIG. 9. (Left.) Plan and vertical section of the Bull Domingo pipe, near Lake City, Colorado.[3] The rock is schist.

FIG. 10. (Right.) Vertical section of the South Ibex pipe, Leadville, Colorado. 1, jumbled quartzite ore, cemented by gold-bearing quartz and pyrite; 2, quartzite; 3, quartzite, crackled and mineralized, but without enough gold to make ore.

[3] Emmons, S. F., U. S. Geol. Survey, 17th Ann. Rept., Part II., 1897.

as subsidence effects. Thus characterized, the pipes in no case show qualities that fail to fit into the general scheme, and various qualities, found sporadically, and hitherto not understood, become logical parts of the larger picture.

For example, the sagging of the beds at Pilares, where the top of the pipe is eroded, is accordant in idea with the upward termination of the South Ibex pipe in a dome 450 feet below the surface.

DESCRIPTION BY B. S. BUTLER OF THE CACTUS ORE ZONE.[4]

The Cactus ore zone lies entirely within the monzonite. It is a rather irregular stockwork having a . . . nearly vertical dip, so far as shown by present developments, in which the rock has suffered brecciation, alteration and mineralization. This brecciated rock extends . . . a distance of about 2,700 feet. . . .

Within the ore zone (or stockwork) the monzonite has been brecciated or broken into irregular fragments, varying from a fraction of an inch to several feet in greatest dimension. Some of these fragments have been corroded by the ore solution so that they present the appearance of a boulder conglomerate with the spaces between the boulders partly or entirely filled with ore and gangue minerals. Usually, however, the fragments are angular, as in a typical breccia. In general the breccia in the upper levels is coarser than that lower down, the spaces between the individual breccia fragments are larger, and many of the spaces have not been entirely filled with later minerals. In the stopes above the sixth level the breccia was well exposed but is finer than in the upper levels and contains practically no unfilled openings; the ore minerals have also replaced the rock to a greater extent. On the seventh level brecciation is less pronounced and the ore minerals very generally replace the monzonite. The same is true of the eighth and ninth levels so far as is revealed by the small amount of development.

. . . The principal primary metallic minerals are pyrite, chalcopyrite, and hematite. . . The important gangue minerals are sericite, quartz, tourmaline, siderite, anhydrite, and barite. . . .

[4] Butler, B. S., "Geology and Ore Deposits of the San Francisco Region, Utah," U. S. Geol. Survey, Prof. Paper 80, 1913.

THE PROCESS OF SUBSIDENCE.

The easiest process of subsidence to visualize is that seen in stopes. An opening is made which subjects the rock to stresses exceeding its strength; the rock fails; angular blocks fill the opening and by their opposing pressure so reduce the stresses that the caving at last comes to an end.

Subsidence at a depth of 10,000 feet, though similar in being controlled by the free movement of rock under the impulse of gravity, would differ in detail. The elastic deformation of the

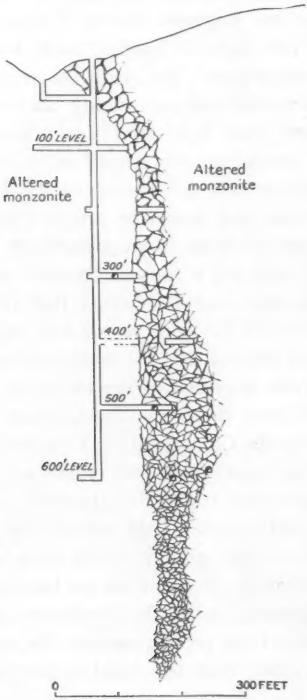


FIG. 11. Plan and vertical section of the Cactus ore zone. (Adapted from Butler.)

rock would be greater and the size of opening that could survive, smaller than that at shallower depth. Were an opening created exceeding that size, as by the solution of a block of limestone or other rock, the unsupported walls would crack and project spalls into the opening, like the walls of deep mine drifts, in which occur "rock bursts"; or, like the walls of the cavities in Bridgman's quartz cylinders, which, when the external pressure was in excess of 4,000 atmospheres, projected into the cavities angular sand grains with such velocity that they cut into and adhered to a copper wire that had been inserted there.[5]

It is of course not supposed that at Pilares, with its cover several thousand feet thick, an opening could have existed equal in area to the present pipe. But, with the supporting pressure, not removed, but merely reduced, widely distributed cracks and minor caves would result and, after a sufficient disturbance of equilibrium, the overlying rock would move downward. The reduction in pressure and the downward movement would, in fact, be simultaneous and would be attended by the successive growth and collapse of caves in large numbers. The now surviving maximum vugs are a foot in diameter and they may be regarded as stable relics and as evidence that all those openings that were larger or that for some reason had weaker walls, were destroyed. It is of interest that the maximum vug in the South Ibex pipe in Leadville is similar in size to that of the Pilares and that the depth of cover there was about 10,000 feet. It is of interest, also, that in the Cresson pipe in Cripple Creek, Colorado, where the depth of cover was only 1,000 or 1,500 feet, the maximum vug was a cave 100 feet in diameter.

In the Pilares, and in most of the others, only the middle section of the pipe is visible and the direct study of that part in which the main shrinkage occurred has not been possible. But in the Catalina in Cananea, and in the Southwest in Bisbee, within a few hundred feet of the present surface, the actual downward terminations are visible; there is a rapid convergence of the walls

[5] Bridgman, Percy, "The Failure of Cavities in Rocks and Minerals under Pressure," *Am. Jour. Sci.* (4), *45*. April, 1918.

forming a rude keel below which the silicified breccia descends only in irregular protuberances. No intrusive plug appears in either case and the hypothesis that such a plug has advanced and retreated is inadmissable. The pipes merely end downward, as they do horizontally, against fresher and less fractured country rock. The curved, marginal cracks are proved by mine workings

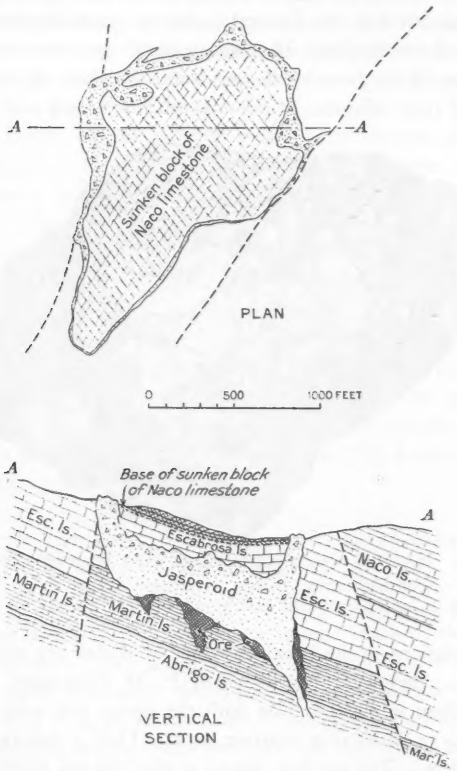


FIG. 12. Plan and vertical section of the Southwest pipe, Bisbee, Arizona. (Kingsbury.)

to terminate with the pipe. The fracturing is not a larger, pre-existing feature along which the pipe was localized, but a property of the pipe itself. The subsidence of these two cylindrical bodies was not something caused by subsidence deeper down, but something due to shrinkage inhering in the pipes and occurring in the region now visible above their rough floors. The facts here indicate the conclusion that is offered as the principal idea of this paper, namely that the mineral bodies in question grew upward through the rock along subsidence cracks: *and that these cracks were created by pressure disturbances attendant on the net removal of rock substance by the mineralization itself.*

FIG. 13. Jasperoid breccia consisting of chert fragments cemented by jasperoid. Southwest area, Bisbee, Arizona. Actual size. (Photo by U. S. Geol. Survey.)

The relations in the Southwest pipe at Bisbee are vital to this discussion; they were determined by H. M. Kingsbury, who has studied them in collaboration with the writer and who will discuss them in detail in a separate paper. Only a general view is needed here. The surface shows a pear-shaped block of flat-lying Naco limestone measuring 1,200 by 2,000 feet, or about the area of the Pilares pipe; surrounding this block are outcrops

of jasperoid, a few inches to 100 feet in width, made up of jumbled, angular fragments of jasperoid and chert tightly cemented by jasperoid, and resembling in structure the Pilares ore.

These jasperoid outcrops follow steep, curved faults and these faults are shown by exploration to go down to the margin of a great body of jasperoid that underlies the Naco area. This body is irregular in thickness; where we know it best it measures 250 feet and replaces the larger part of the flat-lying Escabrosa limestone (the member underlying the Naco) which normally measures 600 feet.

These faults, which are analogous to the curved, marginal faults that go up from the outer edges of a caved stope, are contemporaneous with the replacement of the limestone by the jasperoid. To the process by which such faults are in general made the writer has given the name *mineralization-stoping*, and to the faults themselves Kingsbury has given the name *mineral faults*.

The amount of subsidence in the Catalina is not known. The subsidence in the Southwest, though subject to new estimation after further study, promises to lie between 100 and 300 feet. This was a substitution which took place, not volume for volume, but with a shrinkage of over 20 per cent. and with a minimum net removal of 5,000,000 tons of rock.

CONDITIONS FIXING THE LOCATION AND DIMENSIONS OF A MINERAL PIPE.

If a pipe, rather than an irregular mineral body, is to result, there must be a center of subsidence beyond reach of the effects of other centers. Such a center could be initiated with a cavern or with mere cellularity developed, by the solution of rock adjacent to a channel, to the stage of collapse. Further solvent being provided, stoping could proceed, and this would be arched or domed, whether the progress were downward, outward, or upward. Because of the protection of the floor and side walls by

the weight of the fallen blocks, the progress would in fact be mainly upward.

To what width the stoping would open out before becoming vertical, would depend on a variety of conditions, such as the initial structures, the volume of the solutions, the channels available for their onward travel, and the condition of stress, the elasticity and the solubility of the rocks. In the Southwest area, in Bisbee, it is evident that the solutions worked their way along the flat bottom contact of the Escabrosa limestone for several hundred feet and continued to dissolve the limestone there, per-

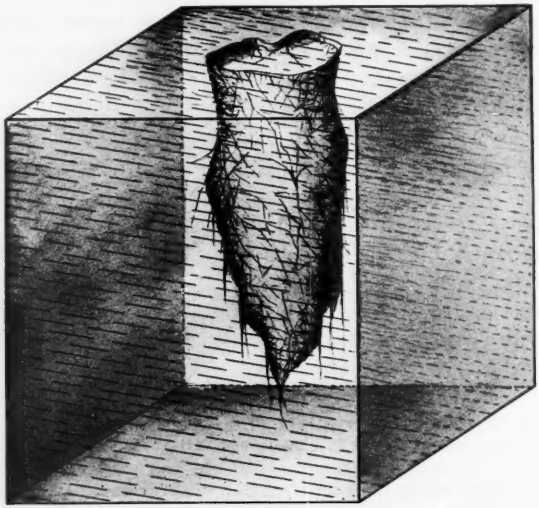


FIG. 14. Diagram of a mineral pipe.

mitting the residual chert layers to fall into the openings, until the whole block sank and steep marginal faults developed. Up to this time, the jasperoid body could have been thin, tabular, and flat. But with the marginal faults available, the volume of solution going upward, and the speed of stoping, could suddenly increase,

the jasperoid body could thicken, and the steep marginal "veins" of jasperoid now showing at the surface could be developed.

In all the pipes, the ore came in at the last stage, after the pipe form had been established, and was localized by some feature of the pipe which happened especially to favor it. For example, in the Southwest area in Bisbee, the ore was made under the jasperoid roof at the contact of jasperoid with limestone. In the Pilares, it was made in the vuggy openings of the marginal, jumbled breccia. In the Catalina, of which only the lower end is left by erosion, the whole pipe was jumbled and vuggy and it all became ore-bearing.

The existence of many blind mineral pipes seems certain, but where to find them is a question which has been answered only vaguely. The best rule now available is to look for them where one or more are already known, for they tend to occur in clusters.

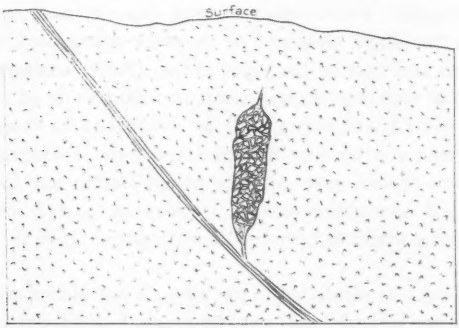


FIG. 15. A mineral pipe stoped upward from a footwall channel and making a structure like that of the Comstock Lode.

All the known pipes lie in brittle rocks and there would seem small reason for expecting them in a soft shale, for example. The pipes occur close to veins and there is evidently some obscure combination of favoring conditions, such as an abundant dissolving fluid so supplied that a single center of solution is established, which determines that a pipe, rather than a vein, or

irregular stockwork, is to result. It is hoped that the knowledge of these favoring conditions will improve. As we learn more of the nature of the mineralizing fluid, from such studies as those by Allen, Day, Shepard, and Zies, it will be of interest to ask, for example, how much of the stoping required in the pipes could have been accomplished by a "gas" and how much must have been accomplished by a denser solution. In this way a closer connection might develop between the pipes and the igneous intrusions.

CONCLUSIONS.

For the mineral pipes, subsidence is the only acceptable explanation. As a cause of this subsidence, mineralization-shrinkage and stoping are established for the Southwest and Catalina pipes and are favored for the others.

The irregular, disseminated mineral deposits have in no case had their shrinkage measured or its cause determined, yet their brecciation and that of the pipes are so closely analagous as to indicate that such deposits in general, including those of Bingham, Braden, and Chuquicamata, will be established as cases of the same process, confused by the overlapping of subsidence circles.

The same process gives promise of application also to the tin-bearing and tourmaline-bearing stockworks, and it may even prove in some places to have been a preparatory stage for igneous intrusion.

The process, as visualized in the pipes, is not incompatible with the movement of rock fragments by pressure developed by growing crystals; but such pressure would be exerted within a body already opened up by subsidence, and would be of minor effect in the final result. Nor is the process incompatible with volume-for-volume replacement, in a particular sense; for, occurring between two flat markers, the stoping can start above the lower and ascend to a dome below the upper and leave both undisturbed.

With volume-for-volume replacement in its strict sense, however, the facts of mineralization-stoping as described in this paper fail to accord. They indicate caving consequent on the

net removal of rock substance, and the final mineral body shows a large increase of porosity, though its outlines may be coextensive with those of the rock body for which it has been substituted.

The facts as described fail to accord also with the idea of mineralization by a fluid that makes the place for new mineral by pushing the rock walls apart. In view of these facts, neither this idea nor that of strict volume-for-volume replacement are to be seriously considered except in those cases where shrinkage is proved not to have occurred.

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METHODS OF PREPARATION OF SEDIMENTARY MATERIALS FOR STUDY.[1]

CLARENCE S. ROSS.

INTRODUCTION.

THE petrological study of sedimentary rocks as a means of solving geologic problems is in greater use today than ever before, but probably none of those interested in petroleum geology, in sedimentary materials, or in soils have made a maximum use of the methods now at the disposal of the petrologist. The isolation and identification of heavy minerals has become a routine procedure in the laboratories of many oil companies, and the study of textural relationships will no doubt be as widely used by the petroleum geologist as soon as the technique of making thin sections of friable materials is better understood. The soil specialist appears to have made even less use of methods that would enable him to make a direct study in thin section of the minerals and original undisturbed texture of soils and clay of porous or friable nature. It is probable that the difficulties involved in the preparation of material for study have been greatly overestimated and all workers will be interested in any methods that improve or simplify the technique. The advance has been so rapid that methods have not become standardized, and the science does not have at its disposal the great number of reference works that are at the command of the student of igneous rock petrology. For these reasons many workers have developed methods that may be of service to others interested in the same field of research.

The petrological laboratories of the United States Geological Survey have been devoting more and more time to sedimentary petrology, and several lines of research have involved the investi-

[1] Published by permission of the Director of the U. S. Geological Survey.

gation of specimens that did not lend themselves to the older methods by which materials were prepared for study. All this has led to a careful survey of petrographic technique and to the development of some entirely new methods, and it seems well to make these available to others. The standard petrographic methods have been described in many textbooks and for this reason there is no need to outline the well known methods for the preparation of material, and the present paper will confine itself to new or little known methods.

MINERAL SEPARATION.

Heavy Solutions.—Many heavy solutions have been recommended at different times, but for most workers the choice seems to have narrowed down to three; that is, bromoform, methylene iodide, and the Clerici solutions. These have been found very satisfactory and to fulfill almost all needs. They are all fairly mobile and mineral grains sink in them with fair rapidity; they are not unduly corrosive and do not actively replace the bases in minerals as does Sonstadt's solution.[2] The cheapest and most widely used of these is bromoform which theoretically has a maximum specific gravity of 2.9. Methylene iodide is rather expensive but is the most satisfactory liquid for separating minerals with a specific gravity up to 3.33. The Clerici solutions that have been described by Helen E. Vassar [3] have a maximum specific gravity of nearly 5.0 and are very satisfactory.

Commercial bromoform can easily be obtained for it is listed in the U. S. Pharmacopoeia. This material, however, contains alcohol and this reduces the specific gravity so that it will often fail to float quartz. In this form it is of little use to the petrologist who usually wishes to separate the heavy minerals from quartz and feldspar. Reed [4] suggests concentrating it by evapo-

[2] Walker, T. L., "Alteration of Silicates by Sonstadt's Solution," *Am. Min.*, vol. 7, pp. 100–102, 1922.

[3] Vassar, Helen E., "Clerici Solution for Mineral Separation by Gravity." *Am. Min.*, vol. 10, pp. 123–125, 1925.

[4] Reed, R. D., "Heavy Mineral Investigations of Sediments." Econ. Geol. vol. 19, p. 326, 1924.

ration, but the bromoform itself is volatile and the method is ineffectual and very wasteful. Bromoform is only slightly soluble in water while alcohol is completely soluble in water, and this provides a simple and effective method for purifying the commercial bromoform. Water is added in excess and the mixture thoroughly shaken and allowed to stand a day or more. At the end of this time the water with the alcohol in solution will have formed one phase and the heavy bromoform practically free from alcohol another phase. The washing may be done in a large beaker and the water decanted, but a large separatory funnel which allows the bromoform to be drawn off at the bottom is most convenient. The heavy phase will contain a little dispersed water but this can be easily removed by filtering through several thicknesses of filter paper. One lot of commercial bromoform examined had a specific gravity of about 2.5 and another of somewhat better grade 2.65 when received from the manufacturer, but after thorough washing and filtering the specific gravity was raised to 2.85.

Methylene iodide rarely falls much below the ideal specific gravity of 3.33. One lot when tested was found to have a specific gravity of 3.28. Methylene iodide that has been held in stock for some time may become very dark colored through the development of free iodine in solution. This is not a serious matter for it becomes clear amber-colored after a few weeks if metallic tin is added, since the iodine combines with the tin to form tin iodide, a light orange-colored salt that is completely soluble in methylene iodide.

When a liquid with a low specific gravity is needed bromoform can be diluted with various solvents, but carbon tetrachloride is probably the most satisfactory as it is cheap, non-inflammable and fairly pleasant to work with. It has a specific gravity of about 1.57 and when mixed with bromoform will give a larger volume of liquid than will be obtained by diluting with a light solvent such as ether which has a specific gravity of 0.71, or benzol with 0.89. Bromoform and methylene iodide can be mixed in all proportions and any intermediate gravity obtained. The addi-

tion of iodoform to methylene iodide will increase the specific gravity to 3.45, but the solution does not filter readily and is unsatisfactory to recover by the methods here described.

SPECIFIC GRAVITIES OF HEAVY SOLUTIONS AND SOLVENTS AT 20° C.

Commercial bromoform	2.5–2.65
Washed commercial bromoform	2.85
Chemically pure bromoform	2.90
Methylene iodide as received	3.28
Chemically pure methylene iodide	3.33
Methylene iodide saturated with iodoform	3.45
Carbon tetrachloride	1.57
Ether	0.71
Benzol	0.89

Recovery of Heavy Solutions.—The capillary spaces between the mineral grains retain rather large amounts of heavy solution and where considerable quantities of minerals are separated the loss may become quite large. Workers are usually advised to wash with ether, benzene, or carbon tetrachloride and to recover the heavy solution by evaporating off the solvent. Methylene iodide is not very volatile and a fair proportion of it can be recovered when the solvents are evaporated, but bromoform is so volatile that a large proportion is lost during evaporation. A far better method is to wash the mineral grains on filter paper with alcohol and later recover the heavy solutions by washing the alcohol out of the resulting solution with water. It is best to give a final washing of the mineral grains with ether to remove the last traces of heavy solutions and to facilitate quick drying. The ether washings usually contain but little heavy solution but sometimes it may be worth while to evaporate and save the heavy residue.

It will be found convenient to keep a large bottle or jar partly filled with water into which the washings which consist of alcohol and heavy solutions can be dumped and cleaned by washing and filtering after a sufficient amount has accumulated. It may be well to keep 2 or 3 such receptacles and to avoid mixing liquids high in methylene iodide with lighter ones.

The filtering and washing of the separated grains is greatly delayed by the use of firm textured filter paper. For this reason the most porous filter paper is preferable, and Japanese lens paper may be used if the mineral grains are not too small.

Separatory Funnels.—Separatory funnels of several designs have been recommended for heavy solution separation, but the long pear-shaped funnel has been most widely used. Holmes [5] mentions the difficulty of washing down the mineral grains when they adhere to the sides of this form, and pictures and recommends a type having the shape of an ordinary conical funnel with a stop cock below. In the design pictured, however, the angle of the funnel walls is altogether too flat and the smaller mineral grains would tend to lodge on the sides and thus fail to reach the bottom. Reed [6] has recommended the use of an evaporating dish instead of a funnel, but in the work in the Survey laboratories a funnel of proper design has been found most satisfac-

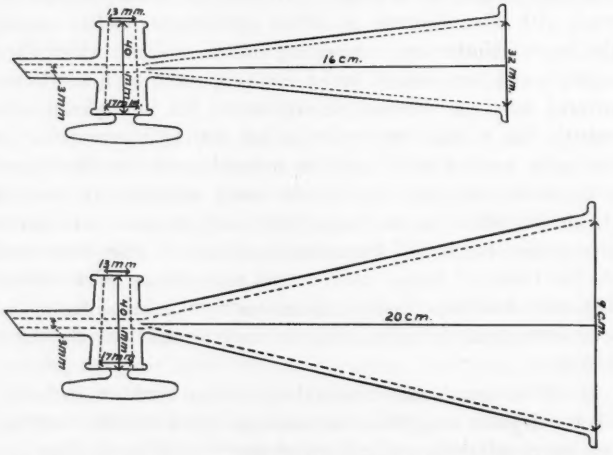

FIG. 1. Separatory funnels designed for mineral separation.

[5] Holmes, Arthur, "Petrographic Methods and Calculations," p. 75, London, 1921.

[6] *Op. cit.*, p. 326.

tory for practically all work and imperative for some. The design that has been adopted is given in Fig. 1. The long sloping sides permit complete settling with no tendency for the grains to lodge on the sides. The open top permits easy stirring and the washing down of grains that have adhered to the sides as the liquid is drained away. The ground flange at the top allows the funnel to be perfectly sealed by the application of a small plate of glass smeared with vaseline. For most work the 3 mm. opening in the stop-cock will be found satisfactory but a 5 mm. opening may be best for some work. The walls of the funnel should taper down to the size of the hole in the stop-cock, so that no shoulder is formed on which grains can lodge. Funnels of this type, made of heavy glass and showing excellent workmanship have been made to order by Emil Greiner, Fulton and Cliff Streets, New York.

Crushing the Rock.—A rock that is to be separated by means of heavy solutions must be crushed sufficiently to separate each individual mineral grain. Extremely fine powder must be rejected and a method of crushing should be followed that will produce a minimum of fines. The most satisfactory method is to reduce the rock to fragments the size of a small pea by pounding with a hammer. These are then placed on a flat steel plate and further crushed by rolling with a steel roller. By repeated rollings and siftings the rock can all be reduced to the desired size and the amount of fine dust will be very small. Often the preliminary pounding will produce more dust than all the subsequent rolling.

Sieves.—Sieves are a necessary part of the equipment of every petrographic laboratory and work can be lightened and results improved by their proper selection. When the sized grains are to be used for mineral identification or accurate analysis it is important to avoid mixing grains from different lots of material even in the smallest proportions. For this reason bolting cloth sieves are more satisfactory than wire sieves. Mineral grains tend to clog the meshes of wire sieves, especially of the finer sizes, but the slightly flexible mesh of bolting cloth is almost free

from this tendency. Before a new lot of material is sieved, it is usually advisable to remove the cloth and free it from all the retained mineral grains by rubbing between the fingers. A very useful set of small sieves that may be used with bolting cloth has been designed by the U. S. Department of Agriculture and manufactured by the Central Scientific Company. These are 1 inch high by 2 inches in diameter and are turned out of heavy brass. The set of 4, the pan and cover all fit firmly and can be shaken as a unit when 4 simultaneous separations are to be made. Bolting silk can not be used where accurate size analyses are to be made and it will often be advisable to divide a lot of material into two portions. One can be used for size analysis with standard brass wire sieves and the other kept free from foreign grains by the use of bolting cloth sieves.

Bolting silk is manufactured in sizes ranging up to 200 meshes per inch and this is fine enough for nearly all purposes. In very rare instances it may be desirable to separate grains down to about 300 meshes per inch, but the wire sieves of that size clog so badly that they are almost useless. It is best to discard the finest material by washing with water in a beaker and allowing the mineral grains to settle 1, 3 or 5 minutes as may be found advisable. By repeated washings and settlings a clean, well-sized product may be secured. Micaceous minerals are the only ones that do not lend themselves to this method for they fail to settle promptly and will be decanted with the sludge.

It is often possible to make a clean separation of micas by alternatingly crushing the rock by rolling on a steel plate and sifting. The brittle grains will be reduced to a powder and can be sifted out, while the flexible mica will be less readily reduced to small size, and will not pass through the sieve.

THIN SECTIONS OF FRIABLE MATERIALS.

Sediments are so variable in composition, texture and coherence that the methods of thin section making that have been developed and found satisfactory for igneous rocks can not always be applied. Limestones, well cemented sandstones and the indurated

shales usually give no trouble when handled by the standard methods, but incoherent sands, tuffs, arkoses, soils, plastic clays, shales and bentonites are not amenable to these methods.

During the past three years the writer has devoted a large amount of time to the technique of thin section making, and as a result the petrographic laboratory of the U. S. Geological Survey has been able to make thin sections of any material that has presented itself, and incoherence, delicacy of structure, and sensitiveness to contact with water have ceased to be a serious handicap. This has been accomplished without elaborate equipment, and by methods that can be easily acquired.

Two main problems are involved in making thin sections of these materials. The first is impregnating with some substance that will act as a binder to give coherence so that the structure will be retained during grinding, and the other is to use grinding media that will not react with the material of the thin section or cause its disintegration.

A number of different materials have been tried for impregnating and binding the porous, friable materials, and two have finally been selected that seem to meet nearly all needs. The most useful of these is the preparation kollolith manufactured by Voigt and Hochgesang.[6a] This is preferred to balsam because it contains no natural turpentine and does not bubble or froth on heating, because it darkens very little on continued heating, and because of its greater toughness or resistance to fracture. Although it has some disadvantages, balsam can be used if kollolith is not available and the technique will be practically the same. The other material is bakelite varnish manufactured by the Bakelite Corporation, Perth Amboy, N. J.

The other equipment needed is a small electric hot plate, two slabs of plate glass, carborundum paper, carborundum, emery or alundum for grinding, a bottle of medicinal petroleum oil (nujol), alcohol, ether, acetone, xylol, slides and cover glasses. A revolving grinding plate is useful but not necessary as the work can usually be done by hand with fair rapidity. Materials con-

[6a] Voigt and Hochgesang, Göttingen, Germany.

taining quartz will grind rather slowly by hand, but carbonates are so soft that they grind with fair rapidity and the hand methods are usually superior to machine methods for clays, shales, and bentonites even when they contain fair-sized mineral grains.

For most purposes impregnating and hardening the specimens by means of kollolith will be found the most expeditious and easily applicable method, and so its use will be described first. Kollolith comes in two forms, one of which resembles cooked balsam, but it is lighter colored and less brittle, and the other is the same material dissolved in xylol.

Preparation and Impregnation of the Chip.—The method of impregnating the pores with binder will vary greatly with the nature of the specimen. Sandy material will usually have fairly coarse pores and will take up the impregnating media readily. The chip may be placed on the electric plate and the heat turned on, and a fragment of hard kollolith placed on top of it. Another method is to place the chip face down in a small metal dish which contains melted kollolith. The capillary force will cause the melted kollolith to penetrate throughout the specimen if the pores are large. The whole operation will not take over 15 minutes and grinding may be begun as soon as the chip has cooled.

Kollolith does not darken or give off distillates at 170° centigrade and so it may be maintained at that temperature for considerable periods of time. It darkens slowly at 200° and so it can be used at this temperature if the heat is not maintained too long, but most claylike materials oxidize and darken at 200° and few specimens will stand that degree of heat for more than a few minutes. For these reasons it will rarely be advisable to exceed temperatures of 150° to 170° for impregnating porous materials with melted kollolith.

Fine-grained compact materials may not absorb the melted kollolith which is rather viscous, and then a solvent must be used to thin it and carry it into the minute pores of the rock. For this purpose the kollolith dissolved in xylol that comes ready prepared may be used, or the hard kollolith may be used and a little fresh xylol added. The xylol-kollolith solution may be applied

directly to the upper surface of the heated chip or it may be placed in a metal dish containing the solution. The xylol is driven off rather rapidly by the heat of the hot plate, but the hot kollolith-xylol solution is rather mobile and penetrates all but the finest grained rocks with fair rapidity. The specimens must be heated for an hour or more to drive off the excess xylol, and the length of heating will depend on the size of the chip and the degree of heat used. These solvents are inflammable and should be used with care, especially when subjected to heat.

Provided a liquid has the power to wet surfaces, its ability to penetrate capillary spaces is a function of the surface tension or capillarity, and the time in which the maximum effect of capillarity is attained is a function of the viscosity. The capillarity of the available solvents does not vary greatly, but the differences in viscosity are very large and therefore low viscosity is the most important factor determining ease and rapidity of penetration of small pores by solvents carrying kollolith or bakelite.

Ether has very low viscosity and penetrates small pores very readily, and it is volatile and can be driven off more rapidly and at lower temperatures than any other available solvent. For these reasons ether has advantages when working with materials with very close textures and where it is advisable to heat the specimen as little as possible. On the other hand, the low boiling point of ether makes it inconvenient to use heat to facilitate penetration. The hard kollolith may be dissolved in ether and then the specimen soaked in the solution in a tightly closed receptacle for 24 hours or more, and afterward the excess of solvent can be driven off by gentle heat. If heat can be safely applied to a specimen ether has little advantage as a solvent for the impregnating media. The viscosity decreases very rapidly with an increase in the temperature, and xylol at its boiling point (140°) would have a viscosity about equal to ether at 20° and but little higher than the viscosity of ether at its boiling point (34°).

VISCOSITY OF SOLVENTS AT 20°.[7]

Water	1.005
Methyl alcohol	.596
Ethyl alcohol	1.200
Ether	.245
Metaxylene (commercial xylol is composed of meta, beta and para xylene and would have a higher viscosity than pure meta-xylene)	.620

The use of bakelite cement for hardening friable materials has previously been described[8] by the writer but the method may be briefly summarized here.

Bakelite varnish is a syrup-like liquid that becomes a very hard, tough resin-like material on the application of heat. The heating first drives off the solvents, but the real hardening is dependent on condensation that results in an entirely new compound. The bakelite varnish contains a little solvent, but it is usually necessary to thin it before it will easily penetrate small pores. Solvents of low viscosity give the best results and so equal parts of methyl alcohol and ether are usually used. Bakelite varnish should be kept in a cool place but it gradually becomes darker and more viscous with age. In this form it does not easily dissolve in alcohol and ether, and forms a white curdy precipitate, but the addition of a small proportion of acetone brings about quick and complete solution. No method of impregnating porous material results in such great coherence, toughness and hardness as the bakelite treatment. The specimen to be impregnated is placed in a dish that can be tightly covered. It is then partly immersed in diluted bakelite varnish, covered and left for 24 hours. It is then removed and allowed to stand a day or two for the solvent to evaporate and finally cured for 2 days at a temperature of 70° to 100° centigrade. It is best to start at the lower temperature and after 6 to 12 hours increase it to 100°. Very friable material that can not stand shaping may receive a preliminary treatment, be reduced to a suitable chip and then receive a final impregnation with bakelite to more completely fill the pores.

[7] Smithsonian Physical Tables, 7th Rev. Ed., p. 158, 1920.

[8] Ross, Clarence S., *Am. Jour. Sci.*, vol. XII., pp. 483–485, 1924.

Bakelite treatment has several disadvantages. Impregnation by this method is time consuming and any attempt to hurry the process will often result in failure. Bakelite has a high index of refraction (1.63) and this is often an undesirable feature. The advantages are, very great coherence, hardness and resistance to fracture. Bakelite shows no tendency to melt, and the hot material is as tough and resistant to fracture as the cold. The high index of refraction is sometimes useful as it accentuates relief and makes pore space stand out with great clearness, and it reduces the relief when used to mount minerals with a high index of refraction.

Impregnation under vacuum may be useful for some materials with unusually small capillary spaces. The Bakelite Corporation manufactures a type of bakelite varnish and solvent expressly designed for vacuum impregnation. The material to be treated is placed in an air-tight container, covered with bakelite varnish and solvent and the air exhausted. The capillary spaces are largely freed from air and filled with the impregnating material under the pressure which may be reduced to 13 centimeters before boiling commences at room temperatures. If necessary impregnation can be still further promoted by applying pressure, after time has been allowed for the maximum escape of air. After complete impregnation the specimen is cured as before described.

After impregnation one surface is prepared for cementation to the slide by fine grinding but the methods will be approximately the same as those used to grind the chip to the proper thinness after cementation to the glass slide. The usual methods of cementing with kollolith or balsam are commonly used but the chip should be heated very gently, as too great heat may cause the kollolith binder to soften and permit the chip to disintegrate. Bakelite does not soften and no special precautions are needed when it has been used as a hardening medium.

Grinding.—The method of grinding the chip to the proper thinness after cementing to the slide will depend upon the nature of the material. Most sands, arkoses, carbonate rocks, and some volcanic tuffs contain no minerals that soften or react with water

and with these the customary thin section technique can be applied. A grinding plate operated by power can be used and is a great help, especially with sections containing quartz or other minerals of marked hardness. However, even these can be made by hand by grinding on a glass plate in a remarkably short time and no one need forego thin sections because of the lack of elaborate equipment.

Most shales, soils, clays, and some arkoses with interstial clay material, and all bentonites contain minerals that soften or swell on contact with water and soluble salts dissolve in water, and for this reason all use of water must be avoided during the grinding operation.

Rough grinding can be done on emery or carborundum paper and a fair degree of thinness attained if the section does not contain large grains of hard minerals that tear loose. The thin section is then ground with oil on a large carborundum hone or the flat side of a fine grained carbonundum wheel and finished on a glass plate. Some liquid must be used with the abrasive powder for fine grinding. After trying many inert liquids, two have been selected that seem to fulfill all requirements.

For hand grinding nothing is superior to the mineral medicinal oils of which nujol is a well known example. It is an odorless oil, it makes a satisfactory liquid to hold the grinding powder, and it is so poor a solvent for balsam or kollolith that it does not soften them seriously while grinding is in progress. These oils vary greatly in viscosity and the light grades are greatly superior to the heavy ones for section grinding. If the section is ground on a revolving plate kerosene should be substituted because the heavy oil makes the section cling to the plate so tenatiously that it can not be held in the fingers but is jerked away with great force. Kerosene is a more active solvent for kollolith and balsam than the oil but if the section is finished quickly little trouble will be experienced from this source. The clays, shales and bentonites grind down so rapidly that hand grinding is usually preferred even though a power operated grinding plate is available.

Carborundum is commonly used for coarse grinding but it is

made up of very sharp, poorly sized grains that cause it to tear delicate sections to pieces, and for this reason emery prepared for optical work will usually give better results.[9]

A few bentonites without gritty minerals and some very fine-grained gritless shales have a texture that allows the making of thin sections without grinding. The chip may be impregnated with the hardening media or not as seems desirable, and is then flattened on one side and cemented to the glass slide. After that it is shaved down with some sharp-edged instrument much as a board is planed down. A glass slide has been found the best for this purpose, but not all slides are suitable as some have the corners too much rounded and others have a ragged edge. If the material is a shale containing minute quartz grains the slide will lose its sharp edge very quickly and a new edge must be used. One advantage of this method is that the work may be done under the microscope with a low magnification and thus all parts reduced to uniform thickness. With care and patience unusually thin sections can be made and there is practically no limit to the size of the thin section that can be produced. Sections 1 x 3 inches have been made without an excessive consumption of time.

Covering the Sections.—Thin sections of friable materials in which kollolith or balsam has been used as a hardening or bonding material, will rarely hold together if the cover glass is cemented on with hard balsam. This method necessitates heating the entire slide, thus softening the material with which the chip was cemented to the glass and also the bonding material within the pores and this usually results in the thin section going to pieces. For this reason the cover glass is almost always cemented with balsam or kollolith dissolved in xylol. It requires some weeks before the section becomes hard enough to stand ordinary handling, but the section may be examined at once if care is used. On the other hand, there is no softening of the thin section if it has been hardened with bakelite, and the section may easily be covered with hard balsam by the usual method.

[9] A table showing sizes and physical characters of various abrasives is given in a forthcoming article, "The Preparation of Polished Sections of Ores," by M. N. Short, which will appear in a later issue of this journal.

Porous materials that have not been impregnated contain a large proportion of pore spaces and even after impregnation there are usually some. These air-filled pores diffuse the light and even a fairly thin section may at first appear opaque. This is especially likely to be observed in sections that have not been impregnated or in those made by the method of shaving down with a sharp instrument. While being ground in oil the pores are largely filled with oil and this reduces or eliminates opacity. Balsam or kollolith dissolved in xylol penetrates the pores after the cover glass has been applied and so the opacity clears up normally. The air in the pores tends to collect as small bubbles under the cover glass and this is a contingency that can not be entirely avoided even when the utmost care is exercised.

CONCLUSION.

The factors that must be considered in making thin sections of difficult materials are, the nature of mineral grains, the nature of the interstitial material between the grains, their reaction to grinding media, and to materials that may be introduced as a binder, and the coherence. These factors vary greatly, and often several must be considered at the same time. For these reasons no routine technique can be followed but each specimen will be a problem in itself, and judgment must be used to determine what materials and methods will give the best results.

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MAGMAS AND IGNEOUS ORE DEPOSITS.

J. H. L. VOGT.

PART III.

CONTENTS—(*concluded*).

Pyrohydatogen and the Hydrothermal Ore Deposits.....469
Behavior of the Principal Metals in Magmatic Differentiation and Magmatic Extraction.....478

PYROHYDATOGEN AND HYDROTHERMAL ORE DEPOSITS.

In the middle of the nineteenth century the Saxon[67] school concluded that the veins of lead, zinc, silver, etc., of Erzgebirge (Freiberg, Schneeberg, Annaberg, etc.), Harz (Clausthal, An-

[67] J. E. Spurr, in his short historical sketch in this journal for 1923, p. 617 et seq., gives an apt characterization of the "French school," represented by Elie de Beaumont and A. Daubrée (1841, 1849 and following years), but I cannot agree with his characterization of what he calls the "German school." In 1840 the pioneer Saxon mining geologist, Oberberghauptmann (mining director in chief) F. C. von Beust (1806–1891), put forward excellent and, in the opinion of most people, decisive arguments for the ascension theory, viz. that the veins—with the Saxon lead-silver veins as examples—were filled by ascending thermal solutions, derived from an unknown depth. This theory was accepted and worked out in more detail by a great number of German geologists in the three succeeding decades. I mention especially: Theodor Scheerer (1813–73, German geologist and chemist, 1841–47 professor of metallurgy at the University of Kristiania—and here the predecessor of my predecessor—and later professor at Freiberg); Bernhard von Cotta (1808–1879, professor in Freiberg 1842–74); Hermann Müller in Freiberg (1823–1907); Albrecht von Groddeck (1837–87, professor in Clausthal); and Alfred W. Stelzner (1840–1895, professor in Freiberg).

The theory of the lateral secretion, advanced (1864) by Bischof (professor in Born) attracted little attention in Germany. Its revival (1882–86) by Fridolin von Sandberger (Würzburg, principally stratigrapher and paleontologist) on the contrary, made a great sensation, though it gained few German adherents. It was otherwise in Przibram in Bohemia.

The untenability of the lateral secretion theory applied to the veins of lead, zinc, silver, copper, etc. was proved in detail by Stelzner (in treatises especially of 1889 and 1896). Partly through the destructive criticism of Stelzner and

dreasberg), Przibram (Bohemia), etc., were formed by ascending hot solutions, from depth. The question of the nature of the depth—or the unknown depth—was not discussed at that time. Thirty years ago [68] referring to several previous investigations, I maintained that the heavy metals of the veins here treated were derived as a rule from deepseated magmas, and that the veins were formed by the continued igneous activity, especially by solfatoric or hydrothermal action.

This conclusion applies especially to the tertiary silver-lead and silver veins (carrying some gold) connected with young igneous rocks and deposited at shallow depth (Schemnitz, Kremnitz, Tonopah, Potosi, etc.); to the silver-lead-zinc veins deposited at greater depth (Freiberg, Schneeberg, Clausthal-Andreasberg, Przibram, Kongsberg, Temiskaming, etc.); to the copper veins (*e.g.*, Butte, Montana); to the veins or impregnations of cinnabar (Almaden, Idria, New Almaden, New Idria, Huancavelica, etc.).

The genetic classification, drawn up in the forties by the brilliant master, Elie de Beaumont, in the "*filons stannifères*" and in the "*filons plombifères*" has proved to be justified, even if the Bolivian tin-silver veins [69] form an interlink between the two groups.

partly from the disappointing technical results of divers surveys undertaken in Przibram based on the theory of lateral secretion, by 1895 the theory was dead in Germany.

I myself (born 1858) am Norwegian, of an old Norwegian family, and not influenced by national German interests. As a young man, at the age of 23–24 years I studied in Germany—Stelzner was my intimate "scientific uncle" and I learned much by conferences with v. Groddeck and H. Müller. I also studied in Paris, where I met Daubrée (1814–1896). As I have followed the development of the subject in question both through the literature and through personal study in several mining districts in Germany, I felt induced to give this short historical summary.

Not the theory of lateral secretion, but on the contrary, the theory of ascension, might for the middle and later part of the nineteenth century be designated as the characteristic of the German (or Saxon) school.

[68] *Zeits. f. prakt. Geol.*, 1895, pp. 475–483.

[69] From the geological literature and from private information obtained from Norwegian engineers engaged in mining in Bolivia, I concluded that they are tin veins of the usual type and also tin-silver veins. In the latter, the common mineral association of the tin veins, viz. cassiterite, wolframite, arsenopyrite, etc.

In the Saxon-Bohemian Erzgebirge, the veins of cassiterite—with some arsenopyrite but with only extremely small quantities of copper, lead, zinc and silver ores—are limited to the granites, and their immediate neighborhood. The numerous veins carrying mainly lead, zinc and silver ores, and in some districts also bismuth and cobalt, occur at a greater distance from the granites, often at a considerable distance. They are all younger than the cassiterite veins. According to the Saxon geologists these younger "vein formations" may have had several periods of mineralization.

In Cornwall and in some other districts are "filons stannifères" as well as "filons plombifères," the first occurring within or in the immediate neighborhood of the granites and the latter and younger some distance away.

In the ordinary "filons plombifères" tin is usually entirely lacking and if present at all, it is in insignificant quantity.[70] The above mentioned Bolivian tin-silver veins form an isolated exception.

In most lead-zinc silver veins wolframite (and scheelite) is lacking. When present it is usually as a mineralogical curiosity;

together with quartz tourmaline, topaz, apatite, etc. deposited at a rather high temperature, belong to a first stage of vein filling. Stannite ($SnCu_2FeS_4$), cylindrite ($Pb_6Sb_2Sn_6S_{23}$), franckeite ($Pb_5Sb_2Sn_5S_{12}$) and especially the (hypogene) silver ores proper, tetrahedrite and ruby silver, belong to a *later* stage of vein filling, at a lower temperature.

In Saxony and Cornwall are separate tin-veins and silver-lead veins, the latter always younger. The crucial point with the Bolivian tin-silver veins seems to be that the later metallic solutions which precipitated the complex silver ores, found their way not through separate fissures, but through the original vein fissures, where the minerals of the tin-association had been deposited already.

[70] At Przibram in Bohemia according to smelter returns the ores average about 20 parts of zinc, 0.75 parts of silver and 0.1 part of tin to 100 parts of lead.

The zinc blende of the "pyritic lead formation" of Freiberg contains, according to the investigations of Stelzner, a small percentage of tin, such as 0.2–0.4, partly sulphide of tin chemically replacing zinc, and partly microscopical inclusions of cassiterite. Similar inclusions of cassiterite are also found in the quartz, accompanying the zinc blende. On the other hand in the many other "vein-formations" of Freiberg, Schneeberg, etc. tin as a rule is not present even in traces.

Many European smelters treating these ores report not a trace of tin.

only quite exceptionally is it present in quantity. As a rule molybdenite is also entirely lacking.

So far as I know, borosilicates have never been detected at all in the shallow depth lead-silver or silver-gold veins, with Schemnitz-Kremnitz and Transylvania as typical European representatives. In the deepseated veins we note axinite ($HCa_3Al_2BSi_4O_{16}$) in the silver veins of Kongsberg, and datolite [71] ($H_2Ca_2B_2Si_2O_{10}$) in the somewhat analogous veins of Andreasberg (Harz),—in both places, however, only as mineralogical curiosities. Apatite is completely absent and the same is true of the elements beryllium and lithium.

Thus between the high-temperature veins of tin, wolfram, molybdenite, etc. and the ordinary low temperature hydrothermal [72] veins of lead, zinc, copper, silver (in the Tertiary veins gold also) there exists a series of important chemical differences.

Regarding the latter, I quote from Beyschlag-Krusch-Vogt, textbook on ore deposits (First edit., I., 1910, p. 171, repeated in the second edition):

> These veins may have been filled by ascending mineral solutions connected with a magma—"Herd" (which may be translated 'residual magma') . . . . . and thus *representing one of the last stages of the series of the eruptive processes.*

Thanks to the very instructive physico-chemical studies of Niggli we are now advanced a good step further in the explanation of the origin of these veins.

In the residual magma there is an enrichment of a series of compounds, which do not, or only subordinately, enter into the first crystallizing mineral, and further—presuming a sufficiently high pressure—there is an enrichment of the volatile compounds (H_2O, CO_2, H_2S, HF, HCl, etc., including the chemical "extract" of heavy metals, etc., of the magma).

Then. at Q (Fig. 2) it emits a gas which afterwards, at P, turns

[71] Datolite occurs also in the Lake Superior zeolitic native copper deposits.

[72] Here fluorite which is often present in these veins, sometimes in great quantity, may not be due to a pneumatolytic process, as it normally is, but to the extremely small solubility of CaF_2 in water. Solutions carrying Ca^{++}, Ba^{++}, and F^-, SO_4^{--} must precipitate the two most insoluble salts, CaF_2, resp. $BaSO_4$.

to a liquid, point P with predominant H_2O lying at a temperature of about 400° (or 400–425°). The considerable difference in the tenor of the elements (in the ordinary lead-zinc-silver veins, in most cases, no Sn, W, Mo, Be, Li, B, P at all) and further the considerable difference in the metamorphism of the wall rock (in the lead-zinc-silver veins no transformation to minerals carrying F and B) may indicate that the principal extracting agency has not been HF or HCl, but other agencies, such as H_2O with CO_2, H_2S or KHS, NaHS, etc. In each case, S in some combination may have been important.

The elements extracted from the residual magma may depend on many factors, viz. the chemical composition of the residual magma itself, the quantity of the numerous extracting agencies and their mutual proportion, temperature, and pressure. The original gaseous extracts may thus have been variable.

To a certain extent or under special conditions the escaping gases probably penetrated pores and cracks of the neighboring rocks, where they may have caused *pyrohydatogene impregnation of ores.* In this manner some fahlbands and similar deposits may have originated. For the final precipitation of the substances we may take into consideration the primary depth differences.

The restmagma from which the gases escaped (point Q) may have been situated at a depth of many kilometers perhaps, in some cases, up to 15–20 kilom., and the locality where the gases liquified (point P) at a depth perhaps up to 10–12 kilom.[73] below the original surface now more or less planed down by denudation.

Mining on these veins reaches a maximum depth of only 1¼–1½ and in most cases ½, ¾ or 1 km., a small fraction of the original depth.

Near the original surface a difference of depth, say from 0.5 to 1.5 kilom., may cause a considerable difference in the chemical and physical conditions of precipitation of minerals from the thermal solutions. It is otherwise in deeply denuded districts

[73] An increase of 3° pr. 100 m. gives 400° at a depth of 13.3 km. There is also the increase of temperature due to the igneous activity.

where present mining to a depth of 1 km. means descending from say 6 to 7 km. of the original depth.

As an example of primary depth difference on a grand scale we shall sketch the principal geological features of *mercury deposits.*[74]

1. The mercury deposits of most districts are intimately connected with rather late Tertiary, and Quarternary effusives.

2. Hot springs in many localities occur in the neighborhood, and some are now precipitating a little cinnabar (*e.g.*, Sulphur Bank and Steamboat Springs). On the contrary, similar springs precipitating ores of lead, zinc, copper, etc., have never been found.

3. The cinnabar deposits do not occur in ordinary fissure veins, but in "chambered veins" or more frequently as impregnations in porous rocks or in innumerable small cracks in divers rocks.

4. The mercury deposits as a rule do not continue to any great depth, and many ore bodies become impoverished at a depth of a few hundred meters. The deepest mercury mine, New Almaden (in California), has reached a depth of about 700 m. Almaden (in Spain) is still rich at a depth of about 400 m., but other old mines (Idria in Krain, Huitzuco and Guadalupana in Mexico, Huancavelica in Peru) became impoverished at a depth of from 200 to 350 m.

5. Cinnabar as a rule is the dominant metallic mineral. It is often accompanied by some pyrite (or marcasite), rather often by some stilbite, sometimes also by some livingstonite ($HgSb_4S_7$), while the ordinary minerals of lead, zinc, copper, silver, etc. are quite subordinate or lacking. Thus Cu, Pb, As, Sb, Bi, Ag and Au are entirely absent at Almaden and Idria; Zn likewise at Almaden and in dubious traces only at Idria. The gangue is principally quartz with chalcedony and opal, some calcite, sometimes barite.

6. In the shallow-depth lead, silver, and gold veins some cinnabar and other mercury ores are not uncommon, but in subordinate amounts. And in the deep-seated veins of lead, silver, gold, etc., cinnabar and other mercury minerals, such as coloradoite (HgTe), are rarer. The mercurial tetrahedrite while somewhat more plentiful in certain veins, has never been found in a great quantity.

7. In spite of the strongly pronounced difference in the metal association of the cinnabar deposits and the shallow depth veins of lead, silver and gold, of Tertiary age, both classes of deposits may be found in the

[74] See the handbooks of Beyschlag-Krusch-Vogt, and of Lindgren, where the previous literature is quoted, further also the explanations given by L. de Launay. I have personal knowledge of Almaden and Idria.

same metallographic province, as in Western Nevada,[75] in Mexico, Peru, etc. In the Carpathians the small mercury deposit of Iglo is situated between Schemnitz-Kremnitz and Nagybanya-Felsobanya-Kapnik, somewhat nearer the former.

Observation 1 above, together with our geological experience in general, prove that the cinnabar deposits are derived from residual magma reservoirs that gave off hot springs, which deposited the mercury rather near the surface, at a low temperature and pressure. The hot springs precipitating cinnabar do not precipitate near the surface sulphidic ores of the much more widely distributed metals, such as lead, zinc, and copper. The thermal solutions that produce the shallow depth lead-silver-gold veins (Comstock, Tonopah, etc.) deposited only rather small quantities of cinnabar, and those that produced the deep-seated veins (Freiberg, Przibram, Kongsberg[76]) on the average still smaller quantities of cinnabar.

The same comagmatic province under certain conditions may produce lead-silver deposits (*e.g.*, Comstock, Schemnitz), with only very small contents of cinnabar, as well as cinnabar deposits, without in many cases even a trace of lead, zinc, copper, silver and gold.

In view of the observations listed above we may accept the ideas expressed some years ago by de Launay, that the solutions, which near the surface gave rise to the cinnabar deposits, at greater depth originally contained some lead, zinc, copper, silver, gold, etc., also, but that these metals were precipitated, sometimes in determinable quantities before the ascending solutions had reached the mercury zone.[77] And on the other hand, the original solutions, which produced the lead-silver veins—such as

[75] Sulphur Bank lies at a distance of only 10 km. from Comstock Lode.

[76] The native silver of Kongsberg often contains a little mercury, usually less than one per cent.

[77] According to the investigations of G. F. Becker, the reason for these facts may be that the mercury in the solutions existed as the soluble component $HgS.n\,Na_2S$ which first was split near the surface. A solution of this character rather rich in Na_2S (and H_2S), might keep Sb_2S_3 also in solution, while on the other hand metals such as copper, zinc and lead were precipitated at an earlier stage, *i.e.*, at a greater depth.

Kongsberg, Clausthal, Freiberg, Przibram, Schemnitz, Comstock, Tonopah, etc.—may originally have contained more, perhaps much more, mercury than the very small amounts which we now find in these veins.

We shall mention some other hydrothermal deposits carrying practically only a single heavy metal.

At *Kongsberg* the silver ore—native silver and a little argentite—is accompanied by rare zinc blende, galena, chalcopyrite, etc., the quantity of silver at the main period of its formation being even greater than that of zinc, lead, copper, etc. The silver was precipitated totally or almost totally as argentite [78] which afterwards by a reduction process, such as

$$Ag_2S + H_2O = Ag_2 + H_2S + O$$

was transformed in large part into native silver. The gangue is principally calcite, and in the hydrous solution, rather rich in carbonic acid, the silver may have existed as $AgH_2(CO_3)_2$, a rather light soluble salt.

As is well known the silver ore occurs only at those places in the veins where they traverse the " fahlbands," carrying, on the average, about 2.5 to 3 per cent. pyrrhotite, pyrite, a little chalcopyrite.

This fact I have tried to explain by an attack of the weak acid (carbonic acid) of the veins on the sulphides of the surrounding fahlbands, whereby H_2S might be developed, yet in such small amounts that only the least soluble sulphide, viz. Ag_2S, was precipitated, while the contents of Pb, Zn, Cu, etc., would remain almost totally in solution.

Another example: The zeolitic deposits of native copper at Lake Superior carrying gigantic quantities of copper, and at numerous other localities, with the same geological and mineralogical features, carrying only small quantities of copper—are intimately connected with basic flows. There are many reasons for concluding that the copper was not extracted from the already solidified rock, but from the magma reservoir, at a period near point Q in Fig. 2.

[78] See my treatise in *Zeits. f. prakt. Geol.*, 1899.

Native copper is practically the sole ore-mineral. The deposits contain a little silver but practically no other metals and only traces of rare copper arsenides (Cu_3As, Cu_9As) and copper sulphides. The mineral association demonstrates a hydrothermal formation (between 150 and 400°). The native copper may have been precipitated by reduction, caused by FeO (in ferrous silicates and magnetite). The reducing agency may have precipitated native copper (and the still more electronegative metal silver), but not the more electropositive metals, such as lead, zinc, nickel, etc. Deposits of a single heavy metal may result from originally mixed solutions in different ways—on the one hand from *rest-solutions* (*e.g.*, the cinnabar deposits at Almaden and Idria) which at previous stages may have precipitated their contents of the other heavy metals, and on the other hand from the original complex solutions, by chemical processes that precipitate a single metal [79] (Ag_2S at Kongsberg, native copper at Lake Superior). Further solutions containing a given proportion of the heavy metals, seldom if ever give rise to ore deposits with the metals in exactly the same proportions.

The Tertiary silver and gold veins, deposited at a rather shallow depth, often exhibit the well known oxide and sulphide enrichment, especially of silver, in the upper portions. Further there is also, as a rule, primary depth zoning in which there is a concentration of silver and gold near the surface that dies out at relatively shallow depths. Many veins, rich not only in secondary, but also in primary silver ores in the upper portions change with depth to veins carrying pyritic galena and zinc blende, with a pronounced decrease of silver (and gold).

Similarly the galena-zinc blende veins at Clausthal and many other localities [80] show a pronounced change in the ratio between galena and zinc blende in the deeper zones, the blende increasing with depth while the galena decreases.

Further there is the well known difference between the silver

[79] This is analogous to magmatic differentiation in the restmagma, resp. in the proto direction.

[80] See Beyschlag, Krusch and Vogt, Handbook I., sec. edit., 1914, p. 200, etc.

and gold contents of the deep-seated veins and of the surficial veins. The deep-seated veins we may divide into two, the distinctly gold-quartz veins carrying only a small quantity of silver and the silver or lead-silver veins, carrying only an extremely small quantity of gold.[81]

The surficial Tertiary silver veins, on the other hand, carry a much higher percentage of gold, and these veins gradually pass into silver-gold and gold veins proper. The original magmatic extracts which gave rise to the deposits of Freiberg, Clausthal-Andreasberg, Przibram, Kongsberg, etc., are unlikely to have differed radically in their gold and silver ratio from those which gave rise to say Schemnitz, Potosi, or Tonopah.

In each case we may suppose a medium quantity of gold, in the original solutions varying of course at the various localities. So we conclude that the solutions of Freiberg, Clausthal-Andreasberg, etc., originally carried a higher percentage of gold and mercury, than is now in the veins.

At a rather shallow depth, say from ½ to 3 km., are heavy precipitation of silver ores, accompanied by relatively much gold, but still with only a small precipitation of cinnabar. Near the surface we get a precipitation of cinnabar from solutions from which the original contents of lead, zinc, copper with silver and gold had been practically entirely removed.

BEHAVIOR OF THE PRINCIPAL METALS IN MAGMATIC DIFFERENTIATION AND MAGMATIC EXTRACTION.

Aluminium.—The deposit of cryolite (Na_3AlF_6) at Ivigtut belongs to the geological Sn-W-Li-F group. And the great deposits of emery near Smyrna and on the island of Naxos have been described as contact deposits. In by far the most contact

[81] As to details see Beyschlag, Krusch and Vogt, textbook. The average ratio of gold, to silver in parts per hundred amounts to:

Kongsberg	about 0.01 gold
Przibram	about 0.0125 gold
Freiberg	about 0.01–0.02 gold

At Clausthal and Andreasberg, both in the Harz, the figures are similarly small.

aureoles, on the other hand, one cannot recognize any transportation of aluminium at all. In the unique deposits of Ivigtut and Smyrna-Naxos the contents of aluminium may have been derived from the magma. It is possible, however, to imagine the volatile compounds, escaping from the magmas, attacking the neighboring rocks and extracting some aluminium from the latter.

Quantitative chemical comparisons of greisen-zones adjacent to tin deposits, with the original granite, show that the introduced aluminium-bearing minerals of the greisen-zone are not due to a fresh supply of aluminium, but depend on the original composition of the wall rock, with an added supply of only fluorine (and boron). The same conclusion may be applied also to the aluminium-bearing minerals of the vein-fillings.

The zeolites, with exception of apophyllite and some very rare species always carrying some alumina, represent in many cases the ultimate hydrothermal stage of the igneous processes. And the same may be true of the druses of albite and adularia in many granites and in granite and syenite pegmatites.—Divers zeolites occur in many hydrothermal ore deposits (*e.g.*, Kongsberg, Andreasberg, Lake Superior native copper), and in some veins are also other aluminium-bearing minerals, such as albite, adularia (valencianite), etc.

This proves that the hot solutions of the veins now and then contained some alumina and sometimes at any rate this may be due to a magmatic extract. In numerous, in fact in most, hydrothermal veins of zinc, lead, copper and silver, aluminium-bearing minerals are, on the contrary, entirely or almost entirely lacking.

The above facts demonstrate that in spite of its considerable quantity in the magmas—only under exceptional conditions was aluminium extracted from the magmas on any scale, at least by the attack of the volatile magmatic compounds.

Some deposits of corundum are formed by magmatic differentiation, and the above mentioned deposits at Ivigtut and at Smyrna are formed by the continued igneous activity. The deposits of aluminium ore proper, viz. the bauxite deposits are, as

is well known, due to tropical weathering and decay at the surface.

Iron is without comparison the most widely distributed heavy metal, the average contents of the igneous rocks amounting to about 60 per cent. SiO_2, 15 per cent. Al_2O_3, and 7 per cent. Fe_2O_3, FeO (and FeS). The average ratio between iron and the other heavy metals of the igneous rocks is as follows:

In relation to 100 parts of Fe

Mn	about 1.7	parts
Cr	about 0.5	parts
Ni	about 0.2	parts
Co	about 0.02	parts
Cu, Pb, Zn each	about 0.01 (or 0.0x)	parts
Sn	about 0.01 (or 0.00x)	parts
Further Ti	about 7	parts
P	about 1.5	parts
S	about 1.5	parts

Iron is found in all ore deposits and here we shall mention only some instances with either very high or very low contents of the metal.

The proto-enriched magmatic segregations within acid rocks at Gellivare carry about 95 per cent. and at Kiirunavaara even 96–97 per cent. magnetite (sometimes also specularite) together with apatite; the last mineral is often present in such quantities as 5–15 per cent., but locally only in very small quantity, and thus we get an iron ore with as much as 69–70 per cent. iron.

The most important deposits of pyrite belong to a special class of magmatic segregations. Deposits of pyrites may also be formed by contact-processes and by hydrometasomatic processes. On the other hand, gold quartz veins, representing the ultimate residual product of acid magmas, and cassiterite veins, due to a fluorine extraction of granitic restmagmas, carry only a small quantity of iron-bearing minerals.

In the ordinary veins of copper, zinc, lead and silver without exception there is some iron, forming pyrite, marcasite, arsenopyrite, pyrrhotite, etc. or entering into chalcopyrite, zinc blende,

etc. Hydrothermal veins of great size and containing almost exclusively iron-sulphides or arsenides are, however, very rare, and the significant feature of these veins is not the presence of iron, but on the contrary, its relatively small amount. Rocks in general carry 1,000 to 10,000 times as much as copper, zinc, or lead, on the other hand, the veins of these metals carry say only 20, 10, 5 or some few times as much iron as the metals just mentioned, and many veins of galena and zinc blende carry even more lead and zinc than iron.

Thus we may conclude that the magmatic extraction processes, acting in the later stages of the solidification of the magmas, as a rule extracted small quantities of iron in comparison to the scarce metals, copper, zinc, lead, silver, etc.

From Beyschlag, Krusch and Vogt, Handbook (II., 1921, p. 747) I abstract a statistical review of the annual iron ore production, from each of the main classes of ore deposits.

Magmatic segregations		
oxide ore	about 5	per cent.
purple ore from pyrites	about 2	per cent.
Contact deposits	about 2.5	per cent.
Siderite veins	about 2–2.5	per cent.
Hydrometasomatic deposits	about 8	per cent.
Sedimentary deposits	about 75	per cent.
Unknown	about 5–10	per cent.

Even if this statement be subject to criticism—and to a yearly revision—it proves the predominance of the sedimentary deposits of iron over those formed in connection with igneous processes.

Manganese.—The percentage of Mn in the rocks averages about 0.08. On the whole it accompanies iron, with certain exceptions. Thus practically no manganese enters into pyrite and only a trifle into magnetite, specularite, and ilmenite. The ferromagnesian or ferrosodian silicates of the anchi-eutectic rocks. rather poor in magnesia, but rather rich in iron (and with a relatively low melting point or interval) show a relatively greater enrichment of manganese than of iron (or of FeO). Manganese, as well as iron, is more abundant in the basic rocks than in

the granites. But on account on the above facts the ratio Mn to Fe, averaging in the igneous rocks 1 Mn to about 55–60 Fe, is altered, in the basic rocks to 1 Mn to about 75–100 Fe [82] and in the acid rocks to 1 Mn to about 25–30 Fe, and in some granitic rocks are ratios of 1 Mn to 10 Fe or 1 Mn to 5 Fe.[83]

In the contact deposits of iron and of other ores manganese is only subordinate. The veins of lead, silver, and gold, often carry some rhodochrosite ($MnCO_3$), those of silver and gold sometimes rhodonite ($MnSiO_3$) also, and as mineralogical curiosities hauerite (MnS_2) and alabandite (MnS) have been found. Further we mention the fairly high percentage of manganese in the siderite of the siderite veins proper. Thus the siderite from the great veins in Upper Hungary contains 1.5–1.75 per cent. Mn and 38 per cent. Fe (or 1 Mn to 20–25 Fe) and the siderite from the very considerable and productive veins in Siegen in Germany on the average 6–7 per cent. Mn and 38 per cent. Fe (or 1 Mn to 5–6 Fe), sometimes even as much as 12 per cent. Mn.[84]

We point particularly to the fact that large deposits of manga-

[82] The titanic iron ores, rich in magnetite and ilmenite, of the magmatic segregations in gabbro, norite, anorthosite, etc. carry on the average 1 Mn to about 150 Fe (see *Zeits. f. prakt. Geol.*, 1900, p. 380). And the iron ores, extra rich in iron from the magnetite and apatite-magnetite deposits within acid igneous rocks carry 1 Mn to about 500 Fe.

[83] This may be the reason for the fact that the secondary deposits of manganese capping silicate rocks, due to weathering, decay, and other chemical processes near the surface, are much more frequent with acid than with basic rocks. See the series of instances enumerated in my treatise in *Zeits. f. prakt. Geol.*, 1906, pp. 231–233.

[84] I call attention to the difference, often overlooked in the American literature, between the *oxidic* and the *neutral* (or reductive) precipitation of iron and manganese from hydrous solutions, carrying carbonic acid. By the *oxidic* precipitation we get: I., hydroxide of iron (together with some silica and phosphoric acid) with only a small amount of manganese. II., The bulk of the manganese, as hydroxide, together with some iron. III., The carbonates of lime, magnesia, etc.—and of course a transition between I. and II., and between II. and III.—By the *neutral* precipitation on the other hand, we get a simultaneous crystallization of $FeCO_3$ and $MnCO_3$.

Thus the oxidic precipitation gives a separation to a great extent; the neutral precipitation on the contrary gives no noticeable separation of iron and manganese. I refer to the reference in Beyschlag, Krusch and Vogt, Handbook (II., sec. edit., 1921, pp. 581–582) or to my previous papers on the problem in question.

nese, in genetic connection with the igneous processes, never have been found,[85] and that the quantity of rhodochrosite and rhodonite in the hydrothermal veins is rather limited.

The bulk of the manganese ore, say, 60 to 75 per cent. of the total yearly production is derived from sedimentary deposits, and the rest from deposits due to rock decay and weathering, from lateral secretion veins, hydrometasomatic deposits, etc., and only a small quantity from deposits which may be due to processes directly connected with the igneous activity.

Nickel, Cobalt, and Chromium.—Nickel and cobalt—average content of the rocks about 0.010 per cent. Ni and 0.001 or 0.0008 per cent. Co—enter quite predominantly into the ferromagnesian silicates (olivine, pyroxenes and amphiboles) on the crystallization of the original magmas. From this cause, the gabbroidic and still more the peridotitic rocks are enriched in nickel and cobalt. Only extremely little of them is left for the granitic rocks, these on the average carrying only about 0.0005 per cent. Ni and 0.00005 per cent. Co, perhaps even still less.[86] The average content of the rocks in chromium is calculated by Washington [87] (1920) at 0.037 per cent. and by Clarke and Washington [88] (1922) at 0.068 per cent. Cr. In my opinion even the first figure is probably somewhat too high. For several chemicopetrographical reasons chromium oxide is concentrated in the gabbroidic and still more in the peridotitic rocks, only very little, probably at the most say about 0.0005 per cent. Cr being left for the granitic rocks.

In the silicates of the Norwegian granitic and syenitic pegmatites not even a trace of either nickel or chromium has been de-

[85] Some lens-shaped and irregular deposits of rhodochrosite, rhodonite and some other minerals, formed in connection with igneous processes, are found in the Huelva district in the South of Spain. These deposits have produced 10,000 or in some years 20,000 tons, of a rather low grade silicious manganese ore. Many years ago (1896) I visited some of these deposits which are the greatest rhodochrosite-rhodonite deposits so far described. But they are not very large.

[86] See my treatise "Nickel in Igneous Rocks," in this journal for 1923.

[87] *Journ. of the Franklin Institute*, 1920.

[88] *Proc. Nat. Acad. of Sci.*, 1922, and *Geophysical Laboratory*, No. 462.

tected (and cobalt only in traces in lollingite). In accordance with the tenor of the metals in the various igneous rocks, the principal ore deposits of nickel—the magmatic segregations of nickel pyrrhotite in norites and peridotites, and the deposits of garnierite, formed by decay of peridotite, etc.—and further the sole class of chromium deposits, viz. the magmatic segregations of chromite in peridotites, occur exclusively in basic rocks.

The other extreme pole of magmatic segregations, viz. the gold-quartz veins, representing the ultimate residual magmatic product of the acid magmas, carry only a trace of nickel, cobalt, and chromium. Further, chromium is practically entirely lacking in all ore deposits resulting from magmatic extraction by volatile compounds. Nickel, and cobalt are practically entirely lacking in the tin-deposits and in the contact iron ore deposits, and present in a small quantity, if at all, in the other contact deposits. In many of the ordinary hydrothermal veins, carrying copper, lead, zinc and silver ores, nickel and cobalt are entirely absent (*e.g.*, Schemnitz) or present in very small amounts (*e.g.*, Freiberg, on the average with only 1/10–1/100 as much nickel + cobalt as silver, and 1/100–1/10,000 as much nickel + cobalt as lead).

In some few ordinary lead-silver veins (*e.g.*, Schneeberg, and Annaberg in Saxony), exceptionally also in some hydrometasomatic zinc-lead deposits (Mine La Motte and Frederickstown in the Mississippi Valley), we meet with more nickel-cobalt, principally as arsenides, and at Mine La Motte as a sulphide, linneæite $(Co, Ni)_3S_4$, the ores in the most cases carrying somewhat more cobalt than nickel. Still greater amounts of arsenides and sulphides of nickel and cobalt occur in the silver-cobalt veins of Cobalt, Ontario, in some veins at Dobschau in Hungary and at Nanzenbach in Nassau. It may not be accidental that the veins of these three districts are connected with basic igneous rock, thus with rocks with a higher average percentage of nickel and cobalt than the more acid rocks.

The quantity of the nickel and cobalt ores in the hydrothermal deposits is, however, on the whole, rather meagre. Thus these

deposits, before the discovery of Cobalt, Ont., produced altogether only about 50 tons of nickel a year out of a total annual production of about 40,000 tons and, in spite of the rather high price of the cobalt some years ago, only about 50 tons of cobalt. At Cobalt, Ont. the quantity of these metals is greater, the content of cobalt in the silver ores mined amounting to 900–1500 tons and of nickel to 350–750 tons a year.

The fahlbands of arsenical ores at Modum, containing about 13 times as much cobalt as nickel, are connected with igneous amphibolites; they may perhaps (?) represent the stage Q–P of Fig. 2.

Tin and Titanium.—Tin is present in traces in all igneous rocks. Thus in the basic rocks there is an extremely small amount of tin oxide entering into the ilmenite of the titanic iron ore segregations within gabbro, anorthosite, etc.—and in the intermediary rocks, we note the very small amount of tin oxide in some minerals (erdmannite, polydymite, etc.) and the mineral nordenskjöldine, $CaSnB_2O_6$, detected by Brøgger in a few individuals in nephelite-syenite pegmatites, representing the rest-magma of the nephelite syenite at a somewhat advanced stage of the solidification. Especially we point out that a little tin oxide, in many cases, 0.01–0.02 per cent. and sometimes a little more, has been detected by several investigators in the feldspars, often also in the micas of the granitic rocks. This last fact justifies the conclusion, pointed out by myself and other investigators many years ago, that the acid magmas are relatively enriched in SnO_2 (in some silicates—feldspar, etc.) by magmatic differentiation.

On the other hand the basic magmas, as is well known, are enriched in titanium as titanic acid.

The intimate connection of the cassiterite veins with granites, and of the Norwegian veins of apatite, rutile, and ilmenite with gabbros, may be due as above explained to a magmatic extraction of compounds of fluorides and chlorides—and this extraction may depend principally on the high magmatic quantity of the halogene compounds, reckoned not only absolutely, but also relatively, to the quantity of H_2O, etc.

In the contact deposits a large amount of titanic acid is extremely rare, most contact deposits carrying only a trifle of titanic acid and practically no tin at all.

And in the veins of copper, zinc, lead, and silver we meet with only a trifle of titanic acid and with a trace of tin or no tin at all. This may be due to the fact that titanium and tin are extracted only in extremely small quantities if at all by the agencies acting on the residual magmas and furnishing the solutions of copper, zinc, lead, etc.

Copper, Zinc, Lead and Silver.—Referring to the methods of investigation used in my treatise on the relative distribution of the minor elements [89] and to the analytical determination of these elements we estimate [90] the average contents in the igneous rocks as follows:

Tin	probably about 0.005	per cent.
Zinc	probably about 0.001	per cent.
Lead	probably about 0.001	per cent.
Copper	probably about 0.000,5	per cent.
Silver	probably about 0.000,005	per cent.
Gold	probably about 0.000,000,1	per cent.

The two last figures are based on the average proportions,
1 part of silver to about 100 [91] parts of copper
1 part of silver to about 200 parts of lead
1 part of gold to about 25–100 parts of gold

further

1 part of cadmium to about 500–1000 parts of zinc,
1 part of selenium to about 5000 parts of sulphur,
250 chlorine: 1 bromine: 1/10 iodine.

Copper occurs in almost all geological classes of ore deposits, viz. magmatic segregations (of nickel pyrrhotite and the intrusive pyrite deposits); contact deposits especially from emanations escaping in the later stages of the solidification of the magmas; cassiterite deposits; these gradually passing into "cassiterite-deposits with copper ore instead of tin ore"; and hydrothermal deposits of various types (Lake Superior, Butte, Chicuquamata,

[89] *Zeits. f. prakt. Geol.*, 1898.

[90] See Beyschlag, Krusch and Vogt, handbook, part I., sec. edit., 1914. p. 157.

[91] Better perhaps about 250 parts of copper and 500 parts of lead.

etc.); further hydrometasomatic deposits (subordinate in the case of copper); the Permian copper schist in Germany (sediment, the contents of copper probably being due to emanations from Permian eruptives), divers fahlbands, etc.

At present the contact and the hydrothermal deposits together furnish about 80 per cent. and the magmatic segregations about 15 per cent. of the total copper production.

A number of investigators have stressed the magmatic sulphidic segregations carrying copper ore and the zeolitic deposits of native copper, both classes of deposits occurring in intimate connection with basic igneous rocks, and from this have concluded that copper is principally a "basic" element. The majority of the contact deposits and of the hydrothermal veins, carrying copper, however, are connected with rather acid igneous rocks,[92] and many of these deposits (*e.g.*, Arizona, Butte, etc.) attain gigantic dimensions. Thus a small amount of copper may be present in the acid rocks also, and we dare not conclude that by magmatic differentiation copper was enriched in the basic rocks; but rather the contrary.

Zinc and lead are practically absent from the nickel-pyrrhotite deposits and only subordinately present in the intrusive pyrite deposits. Further they are almost lacking in the contact iron ore deposits, but are often present in the somewhat younger deposits. Zinc (and manganese) also occurs in the New Jersey franklinite deposits, supposedly due to contact processes. Zinc and lead are scarce in the cassiterite veins; and quartz-tourmaline veins carrying zinc blende and galena are rare. The special homes of zinc blende and galena are the hydrothermal veins representing the last stage of igneous activity, and the hydrometasomatic deposits in limestone—in the United States at numerous localities in the Mississippi Valley, and in Europe in Upper Silecia, Aix la Chapelle and Liège, Carinthia in Austria, etc. This class of deposits, often of a very considerable size, have furnished, in later years, about half of the production of lead and between two

[92] As to details I refer to Beyschlag, Krusch, Vogt, handbook, II., sec. edit., 1921, p. 326 et seq.

thirds and three fourths of the production of zinc, but only very little silver. In many hydrometasomatic deposits silver is entirely lacking. The original source of the metals of these deposits that have no apparent connection with igneous rocks, is in doubt. In Beyschlag, Krusch, Vogt, Handbook (II., 1921, p. 255) it is suggested that the metals may have been derived from a residual magma at great depth, but no decisive argument for this hypothesis could be given.

Silver is constantly present, but only in small quantities, in the magmatic segregations of nickel pyrrhotite, and in the intrusive pyrite deposits. It is entirely lacking in the contact iron ore deposits and as a rule only sparingly present in the other contact ore deposits; further it is practically entirely lacking in the normal cassiterite veins. The bulk of silver belongs to the hydrothermal veins, the Tertiary veins alone furnishing about half of the yearly production of silver, and the veins deposited at a greater depth about a fifth or a sixth. The veins of sulphide copper ores constantly carry some silver, generally about 0.05–0.10, rarely as much as 0.25–0.5 or as little as 0.02 parts of silver to 100 parts of copper. In the zeolitic deposits of native copper also is a little silver.

Gold is primarily at home in the quartz veins and further is present in most veins of lead, silver and copper, but in the deep seated veins of this class it is present only in extremely small amounts.

On the other hand, gold is almost entirely lacking in the cassiterite veins and in the contact deposits of iron ore. In the contact deposits of other ores, gold as a rule is present only in traces.

As to the genetic relation between the shallow-seated gold-quartz veins, with only a small quantity of silver, and the likewise shallow-seated silver-gold veins, this is a difficult question. The last mentioned veins may perhaps (?) be explained by a magmatic segregation of $H_2SiO_3 \cdot nH_2O$ carrying a relatively great supply of volatile compounds.

Platinum metals occur in placers derived from dunites—consisting of olivine rich in Mg_2SiO_4 and very poor in Fe_2SiO_4—

representing the anchi-monomineralic pole of the ordinary magmatic differentiation. In these dunites the platinum metals together with chromite occur as magmatic segregations. The primary deposits of the native platinum metals thus form the very ultimate anchi-monomineralic (or proto-enriched) pole of the magmatic differentiation. Further the platinum metals, especially platinum (as sperrylite, $PtAs_2$) and palladium, are constantly present, though only in small quantity in segregations of nickel-pyrrhotite. The segregations within norites carry on the average 1 part of platinum to 30,000–100,000 parts of nickel[93] and those within "picrite" (or peridotite) at the Insiswa-district in Southern Africa, 1 platinum to about 12,500 nickel. Within the nickel-pyrrhotite deposits the percentage of the platinum metals is relatively highest in those parts richest in chalcopyrite, that means, in those parts which were solidified last. The extremely small quantities of the platinum metals or their compounds, such as $Pt\ As_2$, were thus concentrated in the sulphidic mother liquid.[94]

In some few cases the platinum metals, especially platinum and palladium, have been detected in extremely small quantities in sedimentary or metamorphic rocks and in divers ore-deposits.[95] Thus sperrylite, accompanied by palladium, has been reported from the Rambler mine, Wyoming, in copper ores, probably of igneous origin. As far back as the 1840's the detection of palladium (allopalladium) in a vein of calcite at Tilkerode at Harz attracted great attention. Also in a few other hydrothermal veins, palladium—the most soluble of the six platinum metals—has been found.

But platinum metals are extremely rare in all hydrothermal formations. In the smelting of lead-silver ores the platinum metals if present would be concentrated in the lead bullion and

[93] 1 platinum: 50,000 nickel and 5 per cent. nickel in the ore corresponds to 0.000,1 per cent. platinum in the sulphidic ore itself.

[94] See this journal for 1923, p. 334, and my treatise on the nickel-pyrrhotite deposits in *Norsk Geologisk Tidsskrift*, IV., 1917, p. 38.

[95] See references by Kemp, U. S. Geol. Surv. Bull. No. 193, 1902; Bell, this journal, 1906, p. 749; Clarke, "The Data of Geochemistry," U. S. Geol. Surv. Bull. No. 695, 1920, p. 710; Doelter's textbook of mineralogy, etc.

later in the silver bullion; and from the silver, where gold is extracted, in the gold residues. But the European refineries I have visited, report that as a rule not even a trace of platinum metal can be detected in the gold. In the smelting of nickel-pyrrhotite the platinum metals are concentrated in the first matte, later in the bessemer matte and then again in the nickel-copper alloy; and in refining this alloy electrolitically the platinum metals, platinum and palladium, with only a small admixture of the four other platinum metals and with some silver and a little gold, are recovered with almost quantitative chemical precision.

SUMMARY.

The following is a summary of the relative concentration of the most important elements, on the one hand in the *acid* igneous rocks (the granites, especially the rather acid alkaline granites) and on the other hand in the *basic* igneous rocks (with special reference to gabbros, and peridotites).[96]

In the *acid* igneous rocks are concentrated.	In the *basic* igneous rocks are concentrated.
Silica.	
The alkaline metals, especially potassium (and lithium).	
	Calcium.
Beryllium.	Magnesium, very pronounced.
	Aluminium, slightly enriched in gabbros.
See ratios Fe : Mn.	Iron and manganese.
	Chromium, Nickel & cobalt: strongly enriched especially in the peridotites.
Tin, thorium.	Titanium.
Tantalum, niobium.	
Molybdenum.	

[96] See my previous papers, *Zeits. f. prakt. Geol.*, 1898, p. 325 et seq.: Beyschlag, Krusch, Vogt, handbook I., sec. edit., 1914, p. 160.

Wolfram, uranium, radium,	
Cerium, yttrium, etc.	
Boron.	
Fluorine.	(Chlorine perhaps.)
	Phosphor } enriched in
	Sulphur } gabbros.
Gold.	Platinum metals.

Many investigations seem to indicate that the average contents of copper and silver are higher in acid than in basic igneous rocks.

Except a minute quantity of sodium chloride in the microscopic pores in quartz, etc. and sometimes a little of the alkalies in minerals such as the spinels, potassium and sodium, in the igneous rocks, enter exclusively into the silicates. Calcium (with strontium and barium) and magnesium enter quite predominantly into the silicates, and only subordinately into other minerals;—and aluminium, in a similar manner, predominantly into the silicates, and only subordinately into spinel, corundum, etc. *Chromium* behaves similarly to aluminium, the occurrence in spinels, however, being of more importance.

Iron occurs principally in silicates and in magnetite, ilmenite, specularite, etc. *Sulphur,* averaging about 0.08 per cent. in the igneous rocks, requires not more than 0.07 or 0.08 per cent. iron, thus only 1/70 to 1/80 of the total quantity of iron. *Manganese* occurs predominantly in silicates, subordinate in spinels, etc., and only as traces in the sulphides of the igneous rocks.

The low content of *tin* in the igneous rocks occurs principally in silicates replacing silica, also as cassiterite and in a minute quantity replacing TiO_2, in ilmenite, and rutile.

Zinc is shared between silicates, spinels, etc., and sulphides. *Nickel* and *cobalt* enter predominantly into silicates, especially the ferromagnesian silicates of the basic rocks, and only rather subordinately into the sulphides.

We know some few and extremely rare PbO-silicates, but not, however, in the igneous rocks; further we mention the secondary copper-silicates dioptase (and chrysocolla), the bismuth silicates

eulytine and agricolite, and långbanite, a double compound between silicate and antimonate. Lead and copper are found in small quantity in divers silicates.

As to the allotment of the principal metals between the silicates, spinels, etc., on the one hand, and the sulphides on the other, we may apply to the igneous rocks what we learn from metallurgical processes, especially from the furnace slags.[97]

In blast furnace slags rich in lime and poor in iron and manganese, the dissolved sulphide crystallizes as CaS or (Ca, Mg)S, with a very small percentage of magnesium. With some manganese, we get (Ca, Mn)S, with a relative concentration of manganese in the sulphide; and with a notable content of iron, we get FeS. With a few per cent. of ZnO, say 6–10 per cent. to even as much as 30 or 40 per cent. FeO, the sulphide crystallizing from solution in the silicate melt consists of (ZnFe)S, with more Zn than Fe. And at a temperature of say 1400° this sulphide may be dissolved in basic silicate melts even to the extent of at least 6–7 per cent.—with a sufficient quantity of sulphur or of sulphides the silver content practically entirely, and the copper content almost entirely, enter into the matte. The solubility of Ag_2S in the silicate melts (or slags) is so minute that it can not be determined analytically, and the solubility of Cu_2S is extremely small. CuO may enter into the crystallizing silicates only in a minute quantity. From a melt of Cu_2O and silicate we get a crystallization of cuprite, Cu_2O having no tendency to form silicate compounds.

Lead and nickel are also quite predominantly concentrated in the matte; a little PbO and NiO (and a relatively still higher content of CoO) may, however, enter into the silicate slags. The solubility of PbS, NiS (and CoS) in the slags is small, and very considerably less than the solubility of ZnS.

On account of these facts and a series of other observations we may draw the conclusion, that the extremely small content of silver in the magmas does not enter into silicate compounds, but exists practically exclusively as a dissolved sulphide. Copper

[97] Refer to my many previous studies on this matter.

may exist principally as a dissolved sulphide and only quite subordinately in a silicate compound. Lead exists also principally as a sulphide, but may to a somewhat greater extent than copper enter into a silicate compound. Zinc exists partly as a sulphide and partly as a silicate or an aluminate, and nickel principally as a silicate and only subordinately as a sulphide.

Gold in (primary) ore deposits occurs predominantly as a native metal, and only subordinately in combination with tellurium, further also in pyrite and other sulphides (here probably in a solid solution).—The platinum elements almost exclusively occur as native metals, the ruthenium sulphide RuS_2 and the platinum arsenide $PtAs_2$ being mineralogical curiosities.

As I pointed out many years ago, the reason that the two geological classes of deposits of the platinum metals are both formed by magmatic differentiation, without the coöperation of volatile compounds, and that the platinum metals in ore deposits due to a magmatic extraction by volatile compounds are usually absolutely lacking and when exceptionally present are in very small amounts, must be the extremely high resistance of the platinum metals to chemical reagents. In support of this conclusion we mention that among the six platinum metals it is palladium, with the relatively lowest resistance to chemical reagents, that is sometimes found, and only in very small quantity, in some hydrothermal veins, while osmium and iridium which possess the strongest chemical resistance have not been detected so far as I know even in traces in such veins.

And gold is at home principally in the gold-quartz veins which also may be due to a process of a pure magmatic differentiation, and is relatively subordinate in ore deposits which have passed a gaseous extracting process. That gold in these last named deposits is present in relatively greater quantity than the platinum metals may depend on gold having a lower resistance against the ordinary strong chemical reagents (*e.g.*, aqua regia or chlorine) than the platinum metals, with the exception of palladium.

The deposits of the *native platinum metals* form the *ultimate proto-enriched pole of the magmatic differentiation;* the vein-

dikes of *gold-quartz* (according to the above explanations based principally on Spurr's investigations) form the *ultimate rest-magma enriched pole*. On account of their very low chemical affinities, the platinum metals and gold may exist in the magmatic solutions entirely (or predominantly) as dissolved native metals. The melting points of these metals are:

Osmium	2500°	Platinum	1752°
Iridium	2350°	Palladium	1549°
Rhodium	1970°		
Rutherium, above	1950°	Gold	1062°

In its melting point palladium also stands at the foot of the platinum metals.

The segregation of the platinum metals, with the very first crystallizing minerals, forming as the end product a peridotite (dunite)—and on the other hand, the segregation of the gold in the ultimate residual magma may depend on their great differences in solubility and melting points. When by the refrigeration of the original hot parent magmas the solubility limit of the platinum metals is reached, these separate in the solid phase. Owing to their extraordinarily high density, the platinum metals may subside to hotter zones, where they are resorbed, and by repetition of this process they at last must be enriched in the peridotite magmas.

According to geological observations, the behavior of gold must be quite the reverse. The principal magmatic differentiations take place at a temperature above the melting point of gold. If the solubility limit of gold is reached by these processes, gold may thus be separated in the liquid phase. Yet, the pronounced enrichment in the ultimate residual magma probably depends on the solubility limit of gold not being reached by the magmatic differentiations, the dissolved native gold thus being continuously enriched in the restmagmas up to the last stage, the "aqueous-igneous" restmagma, consisting principally of $H_2SiO_3 \cdot nH_2O$.

We shall now discuss another extreme case.

Aluminium—in spite of its considerable quantity in the igneous rocks, and in spite of the great volatility of the aluminium chloride and fluoride—may be transferred to any considerable extent from the magmas to the neighboring rocks only under unique conditions, and in by far the most pneumatolytic and hydrothermal deposits aluminium is not supplied at all or only in small quantity. These facts mean that the volatile compounds acting on the magmas as a rule extracted only a small quantity of aluminium or no aluminium at all. In other words, the dissolved gases had not sufficient power to split the combination of alumina with silica.[98]

And the practically complete lack of chromium in the pneumatolytic and hydrothermal deposits may not depend on the rather small percentage in the magmas, for chromium is present in much greater quantity than, *e.g.*, zinc, lead, copper and silver. The reason may be that in the magmas, chromium, like aluminium is so strongly combined with silica, that the volatile compounds were too weak to extract it.

The same view may also be applied in the main to vanadium, and with some modifications, to manganese, both elements being still more electropositive than chromium. In spite of manganese being on the average, say 100 times as plentiful in the magmas as zinc, lead and copper, the metal is present on a great scale only in some contact deposits. In most contact deposits and in the hydrothermal deposits, the quantity of manganese is quite inconsiderable, and with some few exceptions much lower than the quantity of zinc, lead and copper.

The metals characterizing the normal tinstone veins are tin and wolfram, thus metals which may have existed in the magma as oxides or oxidic components.

On the other hand, the metals characterizing the hydrothermal veins are principally lead, zinc, copper and silver, further arsenic and antimony, while on the other hand, iron (and manganese)

[98] The alkalies may in part behave in another manner. This is, however, a question which we shall not discuss in this paper.

in comparison to its abundance in rocks is more subordinate.[99] And nickel and cobalt in most hydrothermal veins are either entirely lacking or present in subordinate amounts. In a few hydrothermal deposits, usually connected with basic igneous rocks (gabbro, diabase, etc.), the quantity of nickel and cobalt is somewhat higher, but almost never as high as lead, zinc and copper in their veins.

We call attention to the fact that in the original magmas, lead, copper and silver as also arsenic and antimony exist practically wholly as dissolved sulphides (or in part arsenides, antimonides). Zinc may also to a great extent exist as a dissolved sulphide, though some enters also into silicate or aluminate combinations. The bulk of nickel and cobalt in the magmas enters into silicate compounds, only a relatively small quantity of the two metals existing as dissolved sulphides. Of the total quantity of iron only about 1/75 exists as dissolved sulphide in the magma. Manganese enters the silicate compounds, and only a trifle or none at all exists as a dissolved sulphide. Chromium and vanadium, as also aluminium, calcium, magnesium and the alkaline metals do not exist as dissolved sulphides at all.

Thus we arrive at the conclusion that those metals, which first and foremost characterize the hydrothermal veins, whose metals were extracted in the final stage of the solidification of the magmas (point Q), existed in the magmas principally as dissolved sulphides. This again leads to the *working hypothesis that the chemical agencies, which at point Q furnished the material of the normal hydrothermal veins, extracted principally the dissolved sulphides.*

The study of the genesis of the ore deposits is still in the incipient stage. We can draw up a series of main lines, we can explain some details, but on many questions vagueness still prevails. "We know in part."

But at the same time we have this satisfaction that comparing

[99] Iron and manganese are the principal heavy metals in the siderite veins. It is however, an open question, if the contents of iron and manganese on these veins are derived from the magmas.

the status of this branch of science in 1924 with its status twenty, thirty, forty or more years ago, each decade shows a great advance, and in the future this progress will continuously increase.

In ore deposits as in petrography, we now have a new weapon, viz. physical chemistry, and coöperation between the latter and field observations no doubt will overcome in the future many problems which now seem invincible.

TRONDHJEM, NORWAY.

EDITORIAL

ON TEACHING ECONOMIC GEOLOGY.

POSSIBLY, under pressure from an inexorable editor to deliver an editorial by a certain date, an associate editor, who late in life has turned his attention to teaching, may be pardoned for indulging somewhat informally and personally in a few of the thoughts suggested by his change in occupation. Perhaps these comments may bring out, in the department of *Discussion,* some observations on the above topic by others who at one time, more or less remote, have also discovered that economic geology is not an easy subject to teach and have gained from experience valuable hints that they can pass on to their colleagues.

An initial difficulty is that this branch of geological science is far less thoroughly organized than physics, chemistry, botany or zoology. There is not, as in those sciences, a recognized order of steps up which the student must approach mastery of the subject nor is there a more or less traditional procedure to which most instructors conform. As was emphasized in a previous editorial,[1] economic geology is a relatively new branch of science and one in which hypotheses preponderate over well-established principles. How shall we present to students a subject in which there is still such diversity of opinion in regard to theoretical questions? The geology of metal deposits is fairly well articulated by community of origin, either known or supposed; but how shall we teach and make interesting information concerning that hodge-podge of diverse materials comprised under the designation *Non-Metalliferous deposits,* including building stones and diamonds, asphalt and clays?

The most interesting problem presented by any mineral deposit to the scientific mind is usually "How was it formed?" or "How did it originate?" but to many of the young people of today the questions "Where is the material found?", "What is

[1] This journal, vol. XX., p. 485, 1925.

it good for?", "How can I discover new deposits?" and "How can I turn them to industrial use?" appear to be the more obvious and important inquiries. How shall we, as teachers of economic geology, adapt our instruction to these different points of view? How far, in discussing the economic geology of building stones, shall we consider, on the one hand, the origin of igneous rocks or the processes of erosion and sedimentation and, on the other hand, the technology of quarrying and the problems of marketing? The foregoing are some of the questions that immediately confront the teacher of economic geology. The answers to them depend primarily upon our fundamental concept of education.

Whatever may be the purpose of a vocational or technical school, the function of a university is clearly something higher and broader than merely training men to operate a transit, make assays, construct bridges, or grow oranges. The university ideal should be to develop young men and women intellectually, morally, and physically so that they not only know how to use their minds, in Huxley's phrase "as cold logical engines," but have the moral and physical strength to apply that knowledge wisely to the affairs of life. The educated man is he who through knowledge of the operations of nature and with a sympathetic understanding of the thoughts, words, and deeds of past generations of his fellows, as expressed in history, literature, and art, is able to think straight, to choose in life the things that are really worth while and to find his enjoyment in those pleasures that are noble and lasting—that leave some permanent good behind them, rather than in those that are merely trivial and evanescent. This power of wise choice, based on sound thinking, is probably the most valuable result to be gained from university study and contacts. Its acquisition involves of course self-discipline in methods of intellectual work, the practice of consecutive thought, and, to some extent, the training of the memory. The intellectual worker who can not remember how and where to find the materials he needs or can not carry a number of pertinent facts in mind is like a carpenter who spends his time looking for misplaced tools.

If these general considerations are true, then clearly the effort

in teaching economic geology should be directed toward getting the students to find out things for themselves and to reach their own conclusions rather than to accept passively facts and conclusions, rather than to accept passively facts and conclusions from the instructor. This undoubtedly is far more difficult for the teacher than the simple lecture or textbook method of instruction, which may readily become mere routine. When a number of active minds are gathering information and doing their own thinking, the instructor is kept on the alert to answer questions and to bring out this man's reasons for accepting or that man's reasons for rejecting some particular explanation.

It is apparently consistent with the university ideal to make plain that economic geology is not merely "applied science" but that it is replete with problems that can be solved only through the application of strictly scientific methods by minds equipped with the same kinds of insight and imagination that have contributed to the advance of so-called pure science.

Obviously the university ideal of education has no place for dogmatism or for the statement of disputed conclusions in a loud voice and in a firm and positive manner. If there are differences of competent opinion concerning the way in which this or that ore deposit was formed, the student will probably find this out later and certainly no obstacle should be placed in the way of acquiring this information as soon as possible. He should be encouraged to think about the problem himself. It is incumbent upon the instructor to see that his own views on the matter are clearly presented but not to insist upon them as the only ones entitled to any consideration. Is not the desired relationship between professor and students one in which they regard him not as an infallible authority but as a man who, although older and more experienced than they, is with them a humble and zealous seeker after truth?

The problem of interesting students appears to be less obtrusive in the universities of the western United States than in those of the older and more thickly settled communities, probably because a larger proportion of the men have a fairly definite idea of what

they want and are not merely going through college for social reasons or because it is a tradition in the family. Many of them also are working and paying for their educations. By all means let us make our courses in economic geology as interesting as possible by clear exposition, by lively discussion, and by realization of the motto of Sigma Xi—Companions in zealous research; but efforts to fillip jaded attention by sensational means or to hold it by amusement are inconsistent with the university ideal.

In the affairs of the world and especially in international relations, mineral resources are likely to play an increasingly important and critical part. In the development and utilization of these resources geologists and engineers will be influential in proportion to the extent to which they live up to the university ideal in education. The great work will be done by those who have a broad knowledge of men, of history and of economic forces, who can think straight and can express their thoughts with clarity, precision and effectiveness. The mere technically trained or technically-minded man will probably remain a useful carrier of bricks and mortar. The question whether our civilization is to survive through the discovery of better means of settling disputes than by war or is to go down in ruin through the rapidly increasing power of destruction that is being provided by science and invention, does not depend fundamentally upon politicians. The decision of this question lies in large measure with the economic geologists and engineers who have the vision to see their opportunities of serving humanity.

With this thought in mind, it is not difficult to see how greatly interest in economic geology may be increased by directing the attention of students to the bearing of mineral resources upon the future of the human race. Problems concerned with the origin of mineral deposits become linked with those that underlie distribution and utilization and these in turn with those concerned with the welfare and progress of mankind. It is less than ever sufficient to confine attention to the deposits of one's own country. The problems are world-wide and include the discovery of new resources as well as the utilization of those that are known.

F. L. RANSOME.

DISCUSSION AND INFORMAL COMMUNICATIONS

REPLACEMENT IN TIN BEARING VEINS.

Sir: Studying interestedly the paper of Prof. Waldemar Lindgren on the above subject in the March–April 1926 issue of ECONOMIC GEOLOGY, I was surprised not to find anything in the descriptive portion of the paper which bore upon the subject.

The veins under discussion are presented to the reader as follows: "The width averages a few feet and *the ore is fairly sharply separated from the altered country rock.*[1] However, the veins are almost wholly replacements along narrow fissures, the ore itself containing much black or brown felted tourmaline, with quartz, honey brown or yellow cassiterite, some chlorite, and a little pyrite and sphalerite." The reader peruses further as to the evidence of replacement; but finds no descriptive matter bearing on the subject. The altered country rock (granite) passes gradually into fresh granite. Concerning one of the veins studied the author says:

> The Llamero, with which some of the analyses deal, is a narrow vein striking N. 40 deg. E., 30 to 80 centimeters wide, with massive gangue of black tourmaline, quartz and some pyrite, and contains a granular brown cassiterite and a little wolframite; the vein is adjoined by a few feet of grayish-green altered granite, bordering against fresh granite by gradual transition.

And it is the alteration of the wall rock that forms the whole study of the paper. It is shown that the alteration has produced much chlorite and sericite in the wall rock; and that the chemical changes have involved the loss of all of the soda, most of the lime, and some of the potash, while iron and water has been added.

[1] The italics are mine. J. E. S.

The author observes, "The altered country rock contains but little tourmaline, pyrite, and cassiterite." No evidence as to the structure or origin of the vein itself is submitted.

The description, so far as it goes, gives a picture quite different from the author's "story of genesis" given in the summary. Why the alteration of the granite wall rock (by replacement, to be sure) should be held to be sufficient evidence of the replacement origin of the lode, from which, according to the statements made, it is sharply separated, is a matter of wonderment. Would the alteration, by replacement, of wall rock along a dike intrusion be held to indicate a replacement origin for the dike? Ore magmas in many cases easily accomplish replacement, as I have long and patiently explained; but in the case described by Professor Lindgren, the inference from the facts given is that replacement by the ore magma itself has been very slight. Certainly, the wall rock has been altered and replaced by waters which brought in iron, and abstracted alkalies and lime. These waters may have been residual from the crystallization of the ore magma; or they may possibly have resulted from waters either somewhat earlier or later than the ore-magma injection.

The nature of the Bolivian tin veins is thus described by W. M. Davy:[2] "The veins vary from fissure veins, usually not more than one meter in width, with filling of ore and gangue and with mineralization of the wall of greater or less extent, to mineralized breccia zones, sometimes many meters in width. Crusted fillings of cavities and banded structures in connection with them point to deposition in open fissures, but veins formed by replacement processes also occur."

And Lindgren, in an earlier paper[3] on the tin veins of Chacaltaya, Bolivia, says "the ore forms a filling of open fissures. . . . There appears to be very little alteration in the adjoining country rock."

And F. R. Koeberlin, in an article in the April 17 issue of *Engineering and Mining Journal-Press* on Bolivian tin-bearing

[2] ECONOMIC GEOLOGY, vol. XV, No. 6, Sept. 1920, p. 470.
[3] ECONOMIC GEOLOGY, vol. XIX, No. 3, Apr. 1924, p. 225.

veins, writes: "The veins as a rule fit very well with Spurr's conception of veindikes."

J. E. SPURR.

NEW YORK CITY.

METASOMATISM AND LINEAR "FORCE OF GROWING CRYSTALS."[1]

The Alteration of Plagioclase to Sericite.

Sir: In his discussion on Metasomatism in ECONOMIC GEOLOGY for January–February, 1926, pages 38–40, Mr. H. C. Boydell presents the Lindgren hypothesis of Gel-metasomatism with specific reference to the alteration of labradorite to sericite plus quartz and calcite under the attack of a solution containing carbonic acid and potassium ions. According to this author's conception, solution of the mineral accompanied by hydrolysis results in complete removal of the feldspar and its metasomatic replacement by a mass of alumina-silica gel which eventually gives rise to sericite, any excess of silica appearing as quartz or as opal. With respect to volume the only limitation to be imposed is that the gel may not occupy more space than the erstwhile feldspar.

Consideration of the stated limitation leads me to the conclusion that the process detailed by Mr. Boydell would result in the formation of an extremely porous metasome aggregate quite different from the fairly compact aggregates which the imagined process seeks to explain. To develop the point I have in mind, let it be assumed that the alumina-silica gel contains water in the proportion of three mols for each mol of alumina and of silica. Then it is a simple matter to show that 100 volumes of anorthite or of albite will furnish respectively 197 and 194 volumes of the alumina-silica gel. If plagioclase Ab_1 An_1 is taken, approximately 95 volumes or 47.5 per cent of the total volume of the derived gel must get away, and calculation shows that the remaining alumina and silica will afford about 48 volumes of sericite plus quartz. Thus in the conversion, the shrinkage will

[1] Published by permission of the Director of the U. S. Geological Survey.

account for 52 per cent of the original space, and in the metasome aggregate there will be 52 per cent of voids.

It is suggested that Mr. Boydell's idea of the mechanism involved in the replacement under consideration could be checked by determining the porosity of secondary sericite aggregates of known parentage. Low porosity would argue strongly against the gel replacement hypothesis, while high porosity, though not proving the case, would afford a criterion in its favor.

Relations between solubility and pressure. On pages 11 to 22, Mr. H. C. Boydell discusses the concepts of uniform and non-uniform pressure in relation to solubility, and presents a mathematical treatment of two cases which he groups under the general case of non-uniform pressure. After deriving correct though cumbersome expressions solvable for the ratio dN_2/dP, Mr. Boydell ventures to simplify the result by introducing the assumption that a variable factor entering the expression reduces to a constant, and in this way derives an approximate relation which may be reduced to the form $dN_2/dP = \text{constant}$.

In seeking to understand the problems set by Mr. Boydell, after considerable tribulation I came upon a solution which is algebraically rigorous for both of his cases. This solution depends on the substitution [2] of RT/N_2 for the differential coefficient $(\delta F_2/\delta N_2)$ which enters equations appearing on pages 17 and 21 of Mr. Boydell's text. If this substitution is made Mr. Boydell's Case I. reduces to

$$\frac{d\,ln\,N_2}{dP} = \left(\frac{\partial\,ln\,N_2}{\partial P}\right)_{T\text{ const.}} = \frac{V_1 - V_2}{RT}$$

and his case II. reduces to

$$\frac{d\,ln\,N_2}{dP} = \left(\frac{\partial\,ln\,N_2}{\partial P}\right)_{T\text{ const.}} = \frac{V_1}{RT}.$$

The first expression turns out to be identical with the result derived by Lewis and Randall on page 223 of their book, and it therefore represents the case of uniform pressure. The second

[2] Lewis and Randall, "Thermodynamics," 1925, page 223.

expression represents the only case of non-uniform pressure discoverable by differentiating the equilibrium equation $F_1 = F_2$ with respect to the variables N_2 and P.

On page 13 of his paper Mr. Boydell commends the work of the late Doctor Williamson [3] as being thorough and satisfactory, but apparently he misses the main point of Williamson's discussion which I take to be the contention that the method of analysis adopted by previous workers (and now by Mr. Boydell) involves assumptions in regard to the conditions at a thrust surface which have never been adequately discussed. In the paper cited, Williamson derives separate formulas for the solubility relations at the free surface, and at the thrust surface of a solid under unidirectional compression while immersed in its own solution. The formula for the free surface he regards as allowable but the one given for the relations at the thrust surface he believes to be not admissible because of the doubtful validity of certain assumptions which its derivation involves. This latter formula is readily convertible into an equation identical with the one I have derived for the case presented on page 21 of Mr. Boydell's paper.

Ostensibly the equation which I got by completing the analysis begun by Mr. Boydell should represent the conditions at the free surface, but the identity stated above shows it to represent the conditions at the thrust surface, and so it appears that on the way from definition to differentiation Mr. Boydell has transposed his two cases. As the treatment on page 17 of his discussion is that appropriate for uniform pressure, and that on page 21 applies to Case I and not to Case II (as these are defined on page 15), the conclusions arrived at by Mr. Boydell are seen to be improperly founded.

On page 281 of the paper cited, Williamson gives the relation necessary for transforming his equations into a form comparable with that of the equations which I have given above. Making the indicated transformation and changing from the notation of Gibbs to that of Lewis and Randall, the Williamson equation giving the relations at the free surface becomes

[3] Williamson, E. D., *Physical Review*, vol. 10, pp. 275–283, 1917.

$$\left(\frac{\partial \ln N_2}{\partial P}\right)_{T \text{ const.}} = eP\frac{V_1}{RT},$$

where P is the thrust on the solid, and e is the reciprocal of Young's modulus. This expression differs from the one for the thrust surface only in that the right hand term contains the factors e and P. Thus, the two formulas though quantitatively different are qualitatively similar, and either of them may be read as follows: At constant temperature the change in the Naperian logarithm of N_2 corresponding with any positive finite change in P is positive and dependent upon V_1, the molal volume of the solid salt.

ARTHUR C. SPENCER.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

Sir: I have read with interest Doctor Boydell's article on "Metasomatism and the linear force of growing crystals" in the January Number of Vol. 21 (1926), of ECONOMIC GEOLOGY. The schematic approach to the subject is very helpful, but some of the conclusions do not seem fully justified by the reasoning employed.

The assumption of isothermal conditions is essential to the mathematical treatment on pages 16 and 21, but the argument (footnote, page 3) that isothermal conditions generally obtain should be carefully considered. This argument rests on two assumptions: (1) that the reaction proceeds very slowly, (2) that the temperature of the rock changes very slowly. The first assumption is stated as a fact, but the argument would be more impressive if some evidence were offered to prove its truth. Evidence for the second assumption consists in stating that the operative solutions will generally diffuse with extreme slowness and that heat is therefore absorbed very slowly. The term "diffusing" is confusing to the reader. Is it intended to cover actual movement of a fluid or is the strict meaning of diffusion meant? In either case consideration should be given to the pos-

sibility that metasomatism may frequently take place while the temperature of a rock is being rapidly raised by emanations from an abruptly intruded igneous mass.

In discussing the volume relations involved in metasomatism (pages 4–5), Doctor Boydell assumes that slumping will occur if the space occupied by the palosome is not completely filled by the metasome, but he does not qualify his assumption by admitting that slumping is dependent on the strength of the local rocks. Slumping might occur if the crushing strength were greatly diminished or if the structure of the rock made it especially subject to collapse, but quite commonly a rock may develop a large amount of pore space and show no indication of settling. The dolomitization of limestone is a case in point. Bridgman [1] has shown experimentally that moderately large voids may exist in rocks and minerals under pressures equivalent to the load of many miles of the earth's crust. The effect of fatigue over great periods of time might be expected to cause failure at smaller pressures than those indicated by the experiments cited above, but this effect cannot be of great importance since porous limestones and dolomites occur which were formerly buried to depths of two miles or more.

In the discussion of case III (pages 5–24) (the metasome takes up more room than the palosome) an excellent attempt is made to show that the force of crystallization is not an important factor in vein formation. Since much of the discussion is devoted to refuting the conclusions of Taber, it is regrettable that the references to his work are three times given incorrectly. The paper is contained in vol. 61, 1920, of the *Trans. Am. Inst. Min. Eng.* and not in vol. 51, 1915, as given on pages 6, 7, and 24 by Boydell. It is also worthy of note that no reference is made to the paper of Taber [2] dealing with his experimental work and its interpretation.

On page 23 Doctor Boydell has concisely summed up the objections which may be urged against the theory of vein formation by crystal growth. In examining these objections one should not

[1] Bridgman, P. W., "The Failure of Cavities in Crystals and Rocks under Pressure," *Am. Jour. Sci.*, 4th series, vol. 45, pp. 243–280.

[2] Taber, S., "The Growth of Crystals under External Pressure," *Am. Jour. Sci.*, 4th series, pages 532–556, 1916.

lose sight of the fact that they are not evaluated quantitatively. Thus, (limitation 1, page 23) the *tendency* of pressure is to prevent the freezing of water, but a pressure of 2,000 At. must be used to prevent its freezing at a temperature of —20° C. Limitations 3 and 4 should not be classed as " weighty considerations " since the decreased melting point of a substance caused by either uniform or non-uniform pressure is admittedly of little importance (page 11), and the effect of uniform pressure on the solubility of a substance is minimized in the earlier discussion. The increase in solubility is only 3 or 4 per cent. for pressures running up to 1,500 atmospheres in the examples given (pages 11 and 12).

The case for non-uniform pressure is, at first sight, much more convincing. However, the preceeding discussion of Mr. Spencer shows that Doctor Boydell's case I of non-uniform pressure (page 17 reduces to the expression given on page 228 of Lewis and Randall in their treatment of uniform pressure. This leaves for consideration only case II (page 21). It should be recognized that the *load* placed upon a solid should not be dealt with as a *pressure*. Reference to any standard treatise on the theory of elasticity will disclose the fact that only one-third of a load goes toward a volume change (presssure) in a solid, while the remaining two-thirds of the load tends to change the shape of the body. Since two-thirds of the total pressure is used in setting up strain effects in the solid and since this effect is not evaluated in thermodynamic terms in the case under consideration, it is hard to appraise the significance of Doctor Boydell's treatment of non-uniform pressure. However, if we assume that this treatment is justifiable, it is evident that the resulting equation

$$\left(\frac{\partial \ln N_2}{\partial P}\right)_T = \frac{V_1}{RT}$$

(which Mr. Spencer shows may be substituted for the expression obtained by Doctor Boydell) will give an exponential curve for solubility. The form of the curve indicates a slow increase in solubility with increasing pressure until a certain region is reached

where a small change of pressure effects an enormous increase in solubility. If we plot the curve for naphthaline (data from Lewis and Randall, page 228), we find that the concentration as represented by the mol "fraction" becomes unity at 160 atmospheres of non-uniform pressure and thus the equation becomes irrational for higher values of P. Furthermore, thermodynamic laws only apply rigorously to perfect solutions and as concentrated solutions differ widely from "perfect" solutions, it is obvious that for this reason alone the equation as given above could only be used over a small range of pressures (for other than ideal solutions), if it is applicable at all. It should also be noted that the magnitude of the solubility effect will vary widely with different substances, and the limit imposed by non-uniform pressure on the force of crystallization may range from one atmosphere for one substance to thousands of atmospheres for another substance.

The difficulties of supplying growing crystals with supersaturated solution and the cementing effects caused by non-uniform pressure (limitations 2 and 5, pages 23 and 24) were discussed by Taber[3] in the paper already cited. He describes experiments wherein a saturated solution of copper sulphate, under a head of 20 inches, was permitted to run slowly through a glass tube containing a crystallizing chamber cooled 8° below the temperature of the entering liquid. Formation of crystals in this chamber impeded the movement of the solution but nevertheless the crystals grew and exerted sufficient force to rupture the glass walls. Although the significance of this fact may be overestimated by Taber, any attempt to discredit his results should include a discussion of his experimental work.

On page 27 Doctor Boydell states that solution proceeds "from openings of super-capillary, capillary, and sub-capillary size," which means from openings of *any* size. Apparently in the discussion following, only minute openings are considered. Since it is obvious that reactions between solids and liquids must take place at the contact of the two phases and therefore in "thin films,"

[3] Taber, S., *op. cit.*, page 547, 1916.

one might question the need of emphasizing that "the reactions of metasomatism then take place in thin films" (page 28), as though this fact of itself set them apart as peculiarly different from the reactions with which we are familiar.

The difficulty of supplying a saturated solution to a growing crystal is cited (page 8) as a fundamental objection to the theory that high pressure may be caused by crystal growth; one feels that a similar difficulty is involved in the discussion (pages 30 and 31) where Doctor Boydell justifies the assumption that highly dispersed *colloidal* material can be transported in pores and openings of small size. The impression is gained in this part of the paper that the reactions of metasomatism take place in minute openings through the action of colloidal solutions in process of transport. This impression arises in large part from the summary dismissal (page 30) of molecular and ionized solutions, and the lengthy consideration given to colloidal solutions. The remainder of the paper (pages 30–52) is devoted to the discussion of colloidal phenomena, and the collection of the facts presented is of undoubted value, but the reader gets the impression that Doctor Boydell's bias for colloidal chemistry has prevented a more complete discussion of the part which ionized and molecular solutions may play in metasomatism. It is hoped that this phase of the subject will be discussed by him in the near future.

T. S. LOVERING.

U. S. GEOL. SURVEY,
WASHINGTON, D. C.

SILICIFICATION OF EROSION SURFACES.

Sir: In the article on the above subject by Professor C. K. Leith in vol. 20, No. 6, 1925, p. 518, he says, "the Paleozoic limestones of the Mississippi Valley exhibit widespread, though not universal, silicification of their erosion surfaces." He quotes Ulrich as saying, that within his experience, "most cherts in Paleozoic rocks are sub-aërial weathering products and mainly surficial, extending but short distances into the beds of limestone

however abundantly their exposed surfaces and edges may be studded with chert." It is not clear in the article whether Ulrich's statement covers all the Paleozoics of the entire Mississippi Valley or only those of a limited area. The reference given to Bull. 267, U. S. Geol. Survey, on the "Copper Deposits of Missouri," suggests, however, that his statement refers to Missouri. If so, the writer wishes to express his belief that the field evidence in Missouri is opposed to this view.

Since 1913, the writer has beeen making a special study of the chert in the limestones and dolomites of Missouri. In an article published in 1917 [1] on the origin of chert, Ulrich's view and the evidence against it was given. Deep wells in all parts of the state have penetrated the Paleozoic rocks below the Pennsylvanian, and have proven that chert (also erroneously called flint) occurs to depths of over 2,350 feet. Further, the chert is fully comparable in abundance with that in formations near and at the surface. This abundance is entirely incompatible with the view that the occurrence of chert represents unconformities, for if these occurrences below are unconformities, then each of the hundreds of planes of chert in the exposed section of the Paleozoic also represent unconformities, a view so untenable few would accept it. As pointed out in the paper cited above, the evidence furnished by Lee's own sections [2] is opposed to Ulrich's view, which Lee accepts.

The accumulation of residual chert over cherty formations is a common feature, as Professor Leith states, but the writer does not believe that this accumulation is accompanied by silicification of the upper portion of the limestone in which the chert is found or in the limestone beneath the residual chert. He has studied innumerable contacts throughout the state and has never found such silicified limestone. There is no reason why a certain amount of silica should not pass into solution and be carried into the underlying rocks, and doubtless this is sometimes the case, but this silica forms either chalcedony or quartz, not chert. The

[1] Tarr, W. A., "Origin of the Chert in the Burlington Limestone," *Am. J. Sc.*, vol. 44 (1917), 409–452.

[2] Lee, W., Mo. Bur. of Geol. and Mines, vol. 12, p. 43.

limestone in immediate contact with the cherty mantle rock is absolutely free from any silicification.

Residual accumulations of chert and flint do occur at unconformities, frequently forming a basal conglomerate 50 to 75 feet thick, as, for example, between the Mississippian and Pennsylvanian in Missouri. But can such an accumulation be called a "silicified erosion surface" any more than sand accumulated under similar conditions?

The evidence, as seen by the writer both in the United States and in England, has convinced him that the size or shape of chert and flint nodules, masses, or beds, does not change upon being exposed by erosion, except in the case of the normal mechanical breaking down to fine particles and the leaching of outer surfaces which produces the white marginal zone so common in both flints and cherts.

W. A. TARR.

UNIVERSITY OF MISSOURI,
COLUMBIA, MISSOURI.

REVIEWS

Petroleum in Uganda. Geol. Survey of Uganda, Memoir No. 1, by E. J. Wayland. 4 maps. 61 pp. Entebbe, 1925. Price 5 shillings.

This is the initial Memoir of the Geological Survey of Uganda and its director, Mr. Wayland, has given a thorough treatise on the geology of an all too little studied area of the world, as well as an invaluable study of its petroleum possibilities. The district described is known as the Albertine Depression, and forms part of the Great Rift Valley.

The report is logically assembled. It deals first with the historical outline of events prompting a geological investigation. Under this topic a table of "Mineral Oil Concessions in the Uganda Protectorate" is included. The geology of the district is then treated in a detail that denotes most careful work, inasmuch as a thick vegetation impedes observations.

Briefly, it is shown that a great, but unknown, thickness of shallow water sediments of Miocene, Pliocene and Pleistocene age accumulated in a graben, the Albertine Depression. This rifted valley was formed from crystalline rocks of Proterozoic and Paleozoic age. The Tertiary strata are divided into two formations separated by an unconformity and are overlain in places by late gravels and "red earth deposits." Subsequent tilting has caused a regional dip to the northeast; gentle folding has formed small anticlines of which the axes parallel the valley walls.

The oil possibilities of the Lake Albert Depression are next discussed. A complete summary of this important topic is included in a large table and examination of this table shows that traces of oil were found in 43 out of 52 rock specimens tested. The region is noted for its oil seeps some of which are active and large. There then follows a short "Summary and Recommendations" in which it is pointed out that the oil has apparently been derived from the sediments. This fact and the occurrence of small anticlinal folds leads to a logical recommendation for drilling. Although the exact thickness of the strata is not known, a test well would not exceed 2,000 feet in depth.

The last fifteen pages of the Memoir are divided between four appendices. The first of these discusses briefly the tectonic history of Uganda and also incorporates a table of the geologic history of the dis-

trict. The second appendix deals with the Kaiso bone beds and their faunal content.

The most interesting part of the entire Memoir to the reviewer is contained in Appendix C, entitled "The Origin and Significance of the Lake Albert Petroleum." In this part of the treatise suggestive evidence is advanced that tends to prove that the oil found was generated from materials similar to the thick gelatinous organic matter ("soup") of Lake Albert.

The volume contains many good pictures, charts, cross-sections and tables that augment its clearness. A fairly complete bibliography of publications dealing with the area is most helpful. We welcome this first Memoir and hope there may be later ones as exhaustive of their specific problems.

EDWIN BINNEY, JR.

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Testing and Estimating Alluvials for Gold, Platinum, Diamonds or Tin. By W. E. THORNE. Mining Publications, Ltd., 1926. 52 pp., 9 figs. Price $0.60.

This little book gives specific directions for testing and sampling placer deposits. The author relates in considerable detail the methods he has found most satisfactory for this purpose, describes the best tools to use and gives estimates of costs. His discussion is under the following heads: How to sample; the organization of the drilling party; the drill and its operation; hand drill specifications; instructions for hand drilling, and miscellaneous items, such as removal of boulders, drilling in frozen and swampy ground, pulling the pipe, etc. Though small, the volume contains a great many suggestions that may be of value to the young engineer.

W. S. BAYLEY.

Structure of Herrin (No. 6) Coal Seam Near Duquoin. Report of Investigations No. 5, Illinois State Geological Survey. By D. J. FISHER. Price, $0.25.

The mining of Herrin (No. 6) coal seam near Duquoin is attended with unusual difficulties because of the flexed and faulted structure of this coal bed and the associated strata, and in this bulletin the author sets forth a description of the strata, including both Herrin (No. 6) and Harrisburg (No. 5) coals, a statement and map delineation of the limits of the area underlain by the Herrin coal, a discussion of the areas of split coal and

of the monoclinal and faulted structure, and a statement about the practical economic aspects of the structure. The report is accompanied by explanatory figures and maps, including a map of the Duquoin area showing the structure of the Herrin coal seam.

The Geology of North London. By C. E. N. BROMEHEAD AND OTHERS. Memoir Geol. Surv. of England and Wales, pp. 59, xiii, London, 1925.

This memoir furnishes a brief description of the main features of the geology of an extensive area of London, north of the Thames, and of the surrounding country as far north as Watford and Enfield. In London itself the principal rock is the London Clay, which is covered by various thicknesses of the old river gravels of the Thames. Underneath the clay, at a variable depth, lies the Chalk, which furnishes supplies of water by many deep borings. In the rural and suburban districts the clay again predominates but the Lea valley is bordered by extensive sheets of gravel. On Hampstead Heath the Bagshot Sands occur and near Watford there are small outcrops of the Chalk. At Finchley there is a patch of glacial boulder clay. A new color-printed map has been published of the area described in the memoir, on the scale of one mile to one inch. The revision of the geological information in map and memoir has been very thorough and the work should be useful to architects, engineers, agriculturists, and those in search of a suitable situation for erecting houses or factories. To the geologist who likes to ramble in the country north of London the map and memoir provide the latest information in a handy form.

Geological Map, Union of South Africa. Publications Branch, Govt. Printing Office, Market St., Pretoria, S. A. Size, 6½ by 5 ft.; paper; in colors; scale 15.77 miles to the inch; price £1. 6 s.

This map is compiled from published and unpublished maps prepared by the Geological Survey staff and is the first complete picture of the geology of the Union of South Africa. A small pamphlet that accompanies the map contains a discussion of the physical and geological features and includes a table of formations. The map shows vividly a great curved syncline nearly 1,000 miles long. It presents an excellent picture of the geology and should be useful to students of geology throughout the world.

SCIENTIFIC NOTES AND NEWS

F. L. Ransome, professor of economic geology at the University of Arizona, spent the latter part of June in Butte, Montana, and is engaged for the remainder of the summer in geological work for the Ahumada Lead Company at Los Lamentos, Mexico.

R. E. Somers is head of the department of geology of the University of Pittsburgh. Roswell H. Johnson continues as head of the department of oil and gas production.

J. W. Gruner, of the University of Minnesota, is on sabbatical leave, and will study crystal structure with Professors F. Rinne and E. Schiebold at Leipsig. Enroute, he will present a paper before the Mineralogical Society of Germany at Duisberg.

Seeley W. Mudd, president of the Cyprus Mines Corporation and of the Coeur d'Alene Syndicate Mining Company, and director in the Ray Consolidated, United Eastern and Alaska Juneau companies, died on May 24th after an operation.

J. A. P. Gibb died on March 16 in Toronto, Canada. He was for a number of years consulting engineer of the Anglo-French Exploration Company at Johannesburg.

E. M. Spieker, assistant professor of geology at Ohio State University, recently addressed the geological society at the University of Cincinnati on problems of Cretaceous stratigraphy and sedimentation.

Paul Weaver has resigned from the service of the Cia Mexicana de Petrole, El Aguila, to join the force of the Gulf Petroleum Company at Houston, Texas.

Robert D. Perron has opened an office in La Paz, Bolivia, as consulting engineer.

H. G. Ferguson and J. T. Singewald, after attending the International Geologic Congress, visited the southeastern part of Spain.

Edward Coppée Thurston, mining engineer, died on April 29, at Rose Valley, California, after a long illness.

L. C. Glenn, professor of geology at Vanderbilt University, after making an investigation of new oil discoveries at Sweet Lake, Cameron Parish, Louisiana, recently testified for the Pure Oil Company at Lake Charles in a lawsuit involving the character and origin of Sweet Lake.

A. C. Lawson, at the conclusion of the International Geologic Congress in Spain, sailed from Lisbon for a trip through South Africa.

W. E. Wrather, after leaving Spain, visited the salt deposits of Germany and returned to the United States the middle of July.

At the luncheon of the Society of Economic Geologists held on May 27th in connection with the International Geologic Congress at Madrid, the following members were present:—From Sweden, Per Geijer, Axel Gavelin, H. Van Eckermann; from South Africa, A. L. Hall; from Holland, H. A. Brouwer; from Italy, C. W. Wright; from India, L. L. Fermor; from Canada, E. S. Moore; from the United States, Sidney Powers, J. F. Kemp, H. G. Ferguson, Alan M. Bateman, H. Foster Bain, G. H. Ashley, E. W. Shaw, A. C. Lawson, B. L. Miller, D. F. Hewett, J. T. Singewald, C. A. Bonine, E. B. Mathews, W. E. Wrather.

The following guests were also present: G. W. Grabham, Soudan; H. B. Maufe, Rhodesia; C. Palache and E. H. Sellards, U. S. A.; C. H. Cunningham, Madrid.

The International Geologic Congress at Madrid during May and June had about 1000 registrants, of whom about 350 were non-Spanish. The geological excursions before and after the Congress were so filled that several could not gain admittance. The Moroccan and Huelva trips were particularly popular. The Spanish officials spared no pains to make the excursions interesting and valuable, and the Spanish people and the mining companies of the local communities showed what hospitality could be. Banquets, receptions and Spanish courtesy were interspersed with geology, while Spain's wealth of art and scenic beauty was not overlooked. During the week of the Congress many valuable papers were delivered, but the lounging spaces were more occupied than the session rooms. The elaborate social functions, particularly the reception by the King and Queen of Spain at the Royal Palace, were greatly appreciated by the visiting geologists. All will look forward to the printed volumes of the proceedings.